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WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

# DRAFT
# Wenatchee River Temperature TMDL

## Partial completion of the technical report after the first year of data collection

March 2004

Publication No. 04-xx-xxx

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# Wenatchee River Temperature TMDL

## Partial completion of the technical report after the first year of data collection

*by*

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Washington State Department of Ecology
Environmental Assessment Program

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# Abstract

As part of the Wenatchee River total maximum daily load (TMDL) study for temperature, the Washington State Department of Ecology (Ecology) conducted field work during 2002-2003. This report presents availability and summaries of data collected mainly during 2002 in the Wenatchee River, Icicle Creek, and their tributaries. Aerial thermal infrared radiation surveys through 2003 are also presented. In addition, this report presents an overview of important stream heating processes in the Wenatchee River watershed, as well as the modeling methodology that will be used for the technical study for the TMDL, and preliminary results of the model development to date.

# Acknowledgements

We would like to thank the following people for their contributions to this study:

- Dave Schneider (Ecology) for review of the draft report and coordination of the public review process.
- Karol Erickson (Ecology) for review of the draft report and many valuable comments.
- Joan LeTourneau (Ecology) for report formatting and publication.

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# Introduction

Ecology is required by the federal Clean Water Act to conduct a Total Maximum Daily Load (TMDL) evaluation for all waterbodies on the 303(d) list. The evaluation process includes a water quality technical study to determine the capacity of the water body to absorb pollutants and still meet water quality standards. The study also evaluates the likely sources of those pollutants, and the specific amount of pollution (the pollutant load) that needs to be reduced to meet state water quality standards. During and after the technical study, Ecology works with other agencies and local citizens to identify pollution controls based on the study findings. A TMDL study for the Wenatchee River watershed was begun in 2002, and this report summarizes the results to date.

The Wenatchee River watershed is located in Chelan County. A map of the study area is shown in Figure 1. The technical study to address water quality concerns in the Wenatchee River watershed, also known as Water Resources Inventory Area number 45 (WRIA 45), was split into two years of field data collection. The first study year, with field data collection during 2002, was focused on the mainstem Wenatchee River from the outlet of Lake Wenatchee to the river's confluence with the Columbia River at the city of Wenatchee, and includes Icicle Creek. The second study year, with data collection during 2003, was focused on the other major tributaries to the Wenatchee River. This report provides a partial completion of the TMDL study report with analyses that have been completed through 2003, including mainly field work collected during 2002 as well as aerial thermal infrared and color video remote sensing surveys conducted through 2003.

The 1998 303(d) list for temperature in the Wenatchee River watershed is presented in Table 1. The Department of Ecology is in the process of updating the list of impaired waters for the State of Washington. Following guidance from the U.S. Environmental Protection Agency, the 2002/2004 listing process includes a much more comprehensive assessment of Washington's waters than previous 303(d) lists. The 2002/2004 303(d) list is a work in progress and revisions will be posted on Ecology's Web page (www.ecy.wa.gov/programs/wq/303d/2002/2002-index.html).

Table 1. 1998 303(d) listings for temperature in the Wenatchee River watershed.

| Waterbody name | Township | Range | Section | IIP 303D number | WBID number |
|---|---|---|---|---|---|
| CHIWAUKUM CREEK | 25N | 17E | 09 | HM20EV56.298 | WA-45-1900 |
| ICICLE CREEK | 24N | 17E | 30 | KN36FW12.147 | WA-45-1017 |
| LITTLE WENATCHEE RIVER | 27N | 16E | 15 | DS66LF1.842 | WA-45-4000 |
| MISSION CREEK | 23N | 19E | 20 | DQ04NW5.629 | WA-45-1012 |
| NASON CREEK | 26N | 17E | 09 | FZ91ME0.000 | WA-45-3000 |
| NASON CREEK | 27N | 17E | 27 | UO87HL0.288 | WA-45-3000 |
| PESHASTIN CREEK | 24N | 18E | 21 | OM13EX0.638 | WA-45-1014 |
| PESHASTIN CREEK | 24N | 18E | 32 | OM13EX4.357 | WA-45-1013 |
| WENATCHEE RIVER | 23N | 20E | 28 | HM20EV0.600 | WA-45-1010 |

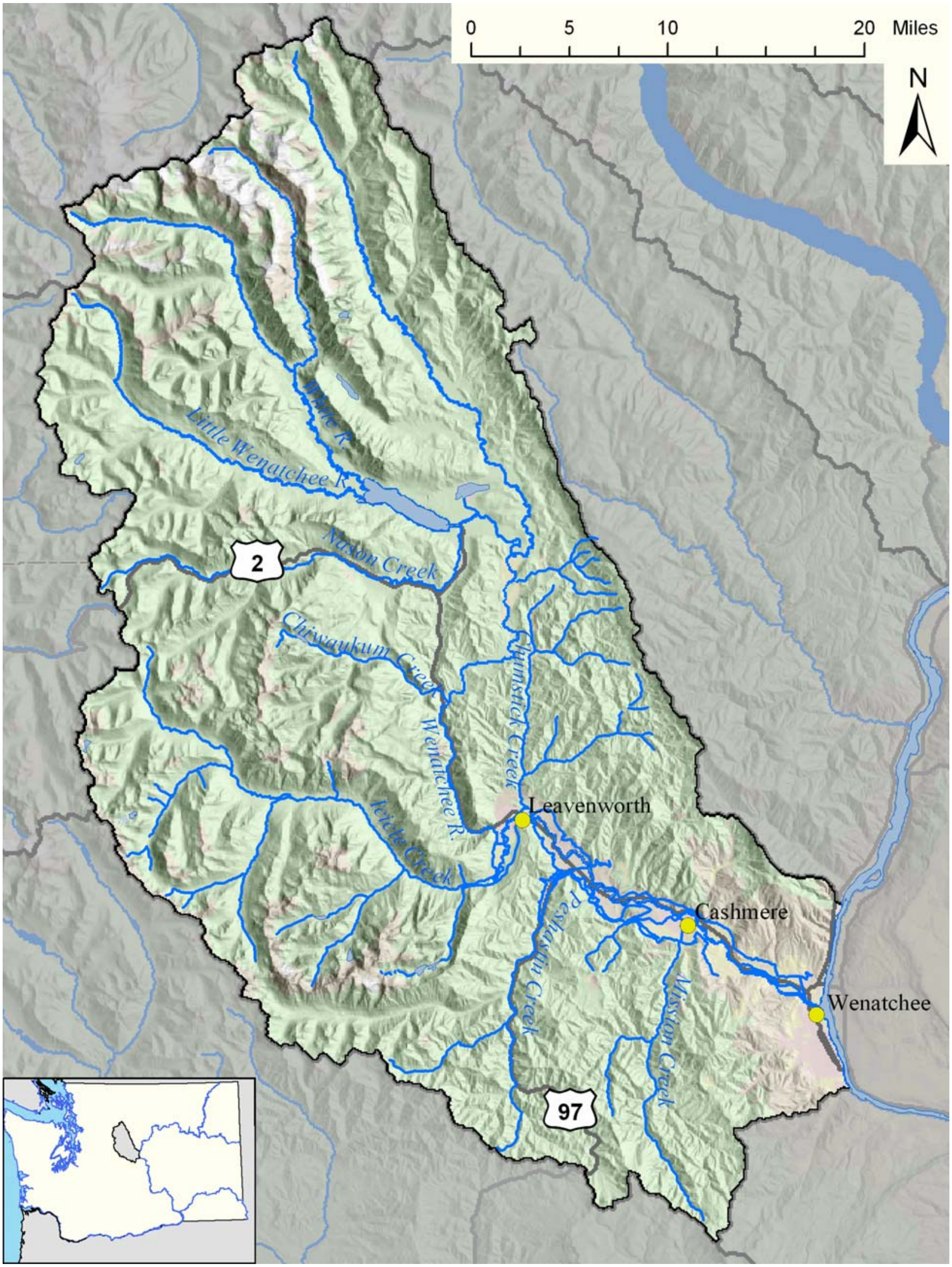



Figure 1. Study area map for the Wenatchee River Temperature TMDL.

## Overview of stream heating processes

The temperature of a stream reflects the amount of heat energy in the water. Changes in water temperature within a particular segment of a stream are induced by the balance of heat exchange between the water and the surrounding environment during transport through the segment. If there is more heat energy entering the water in a stream segment than there is leaving, then the temperature will increase. If there is less heat energy entering the water in a stream segment than leaving, the temperature will decrease. The general relationships between stream parameters, thermodynamic processes (heat and mass transfer) and stream temperature change is outlined in Figure 2.

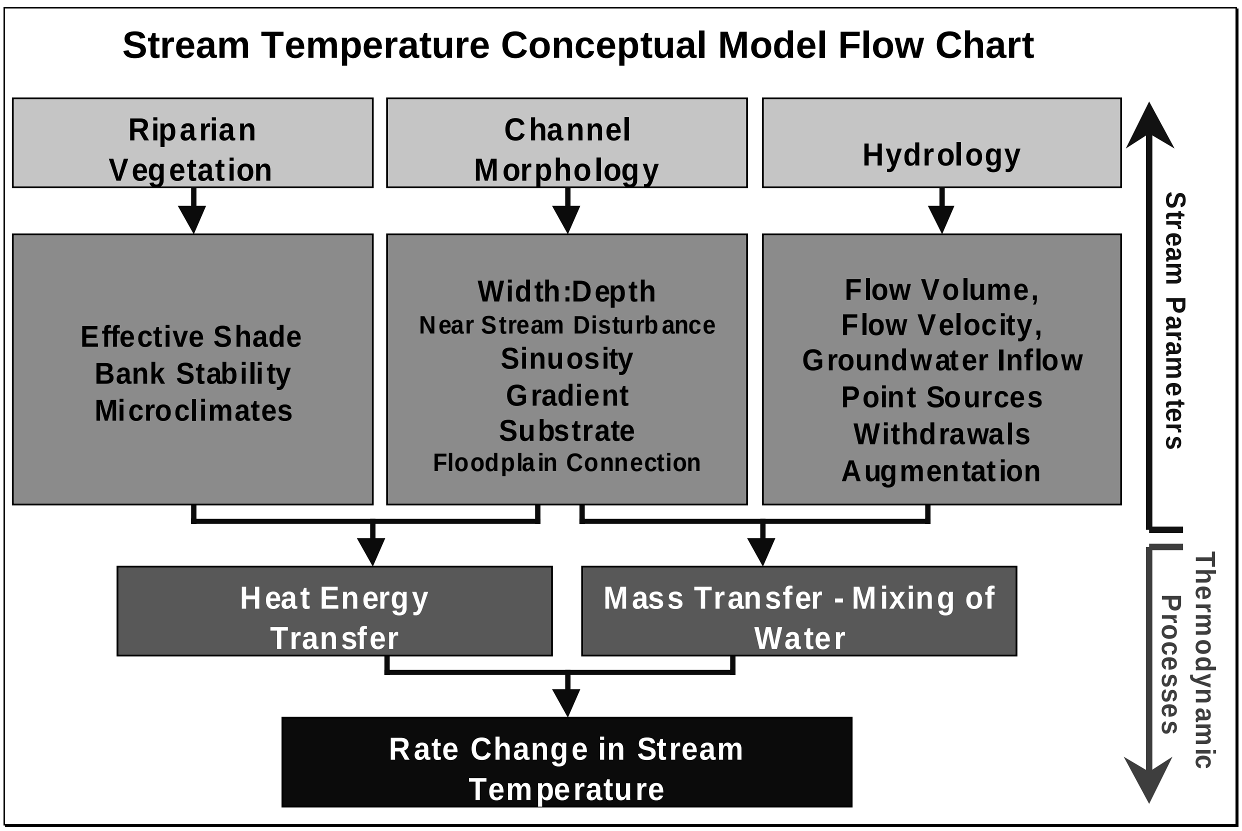



Figure 2. Conceptual model of factors that affect stream temperature.

Adams and Sullivan (1987) reported that the following environmental variables were the most important drivers of water temperature in forested streams:

- **Stream depth.** Stream depth is the most important variable of stream size for evaluating energy transfer. Stream depth affects both the magnitude of the stream temperature fluctuations and the response time of the stream to changes in environmental conditions.

- **Air temperature.** Daily average stream temperatures are strongly influenced by daily average air temperatures. When the sun is not shining, the water temperature in a volume of water tends toward the dew-point temperature (Edinger et al. 1974).
- **Solar radiation and riparian vegetation.** The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar heat flux. Daily average temperatures are less affected by removal of riparian vegetation.
- **Groundwater.** Inflows of groundwater can have an important cooling effect on stream temperature. This effect will depend on the rate of groundwater inflow relative the flow in the stream and the difference in temperatures between the groundwater and the stream.

## Heat budgets and temperature prediction

The transport and fate of heat in natural waters has been the subject of extensive study. Edinger et al. (1974) provide an excellent and comprehensive report of this research. Thomann and Mueller (1987) and Chapra (1997) have summarized the fundamental approach to the analysis of heat budgets and temperature in natural waters that was used in this TMDL. Figure 3 shows the major heat energy processes or fluxes across the water surface or stream bed.

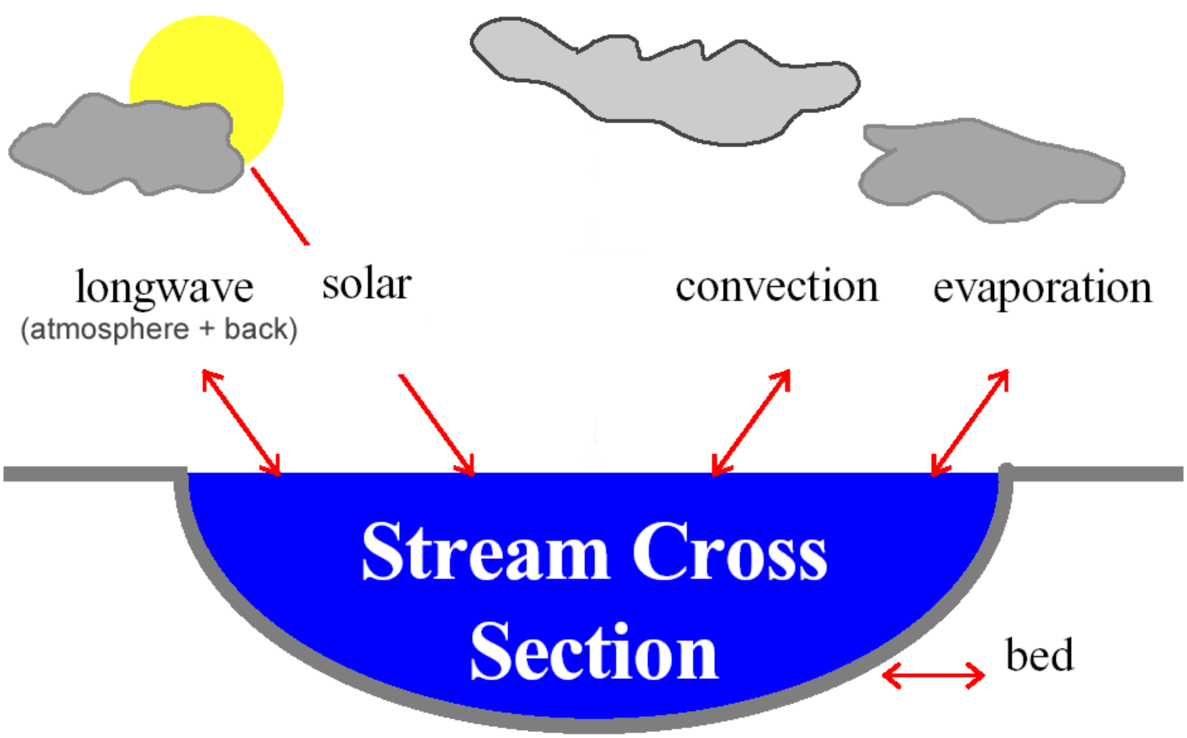



Figure 3. Surface heat exchange processes that affect water temperature (net heat flux = solar + longwave atmosphere + longwave back + convection + evaporation + bed). Heat flux between the water and stream bed occurs through conduction and hyporheic exchange.

The heat exchange processes with the greatest magnitude are as follows (Edinger et al. 1974):

- **Short-wave solar radiation**. Short-wave solar radiation is the radiant energy which passes directly from the sun to the earth. Short-wave solar radiation is contained in a wavelength range between 0.14 µm and about 4 µm. At WSU's TFREC station in Wenatchee the daily average global short-wave solar radiation for August 2002 was 259 W/m2. The peak values during daylight hours are typically about 3 times higher than the daily average. Short-wave solar radiation constitutes the major thermal input to an un-shaded body of water during the day when the sky is clear.
- **Long-wave atmospheric radiation.** The long-wave radiation from the atmosphere ranges in wavelength range from about 4 µm to 120 µm. Long-wave atmospheric radiation depends primarily on air temperature and humidity and increases as both of those increase. It constitutes the major thermal input to a body of water at night and on warm cloudy days. The daily average heat flux from long-wave atmospheric radiation typically ranges from about 300 to 450 W/m$^2$ at mid latitudes (Edinger et al. 1974).
- **Long-wave back radiation from the water to the atmosphere.** Water sends heat energy back to the atmosphere in the form of long-wave radiation in the wavelength range from about 4 µm to 120 µm. Back radiation accounts for a major portion of the heat loss from a body of water. Back radiation increases as water temperature increases. The daily average heat flux out of the water from long-wave back radiation typically ranges from about 300 to 500 W/m$^2$ (Edinger et al. 1974).

An example of the estimated surface heat fluxes in the Wenatchee River near Monitor during August 2002 is shown in Figure 4. The daily maximum temperatures in a stream are strongly influenced by removal of riparian vegetation because of diurnal patterns of solar short-wave heat flux (Adams and Sullivan, 1989). The net heat flux into a stream can be managed by increasing the shade from vegetation, which reduces the short-wave solar flux. Other processes, such as long-wave radiation, convection, evaporation, bed conduction, or hyporheic exchange also influence the net heat flux into or out of a stream.

Heat exchange between the stream and the streambed has an important influence on water temperature. The temperature of the stream bed is typically warmer than the overlying water at night and cooler than the water during the daylight hours (Figure 5). Heat is typically transferred from the water into the stream bed during the day then back into the stream during the night (Adams and Sullivan, 1989). This has the effect of dampening the diurnal range of stream temperature variations without affecting the daily average stream temperature.

The bulk temperature of a vertically mixed volume of water in a stream segment under natural conditions tends to increase or decrease with time during the day according to whether the net heat flux is either positive or negative. When the sun is not shining, the water temperature tends toward the dew-point temperature (Edinger et al. 1974; Brady et al. 1969). The equilibrium temperature of a natural body of water is defined as the temperature at which the water is in equilibrium with its surrounding environment and the net rate of surface heat exchange would be zero (Edinger et al., 1968; Edinger et al., 1974).

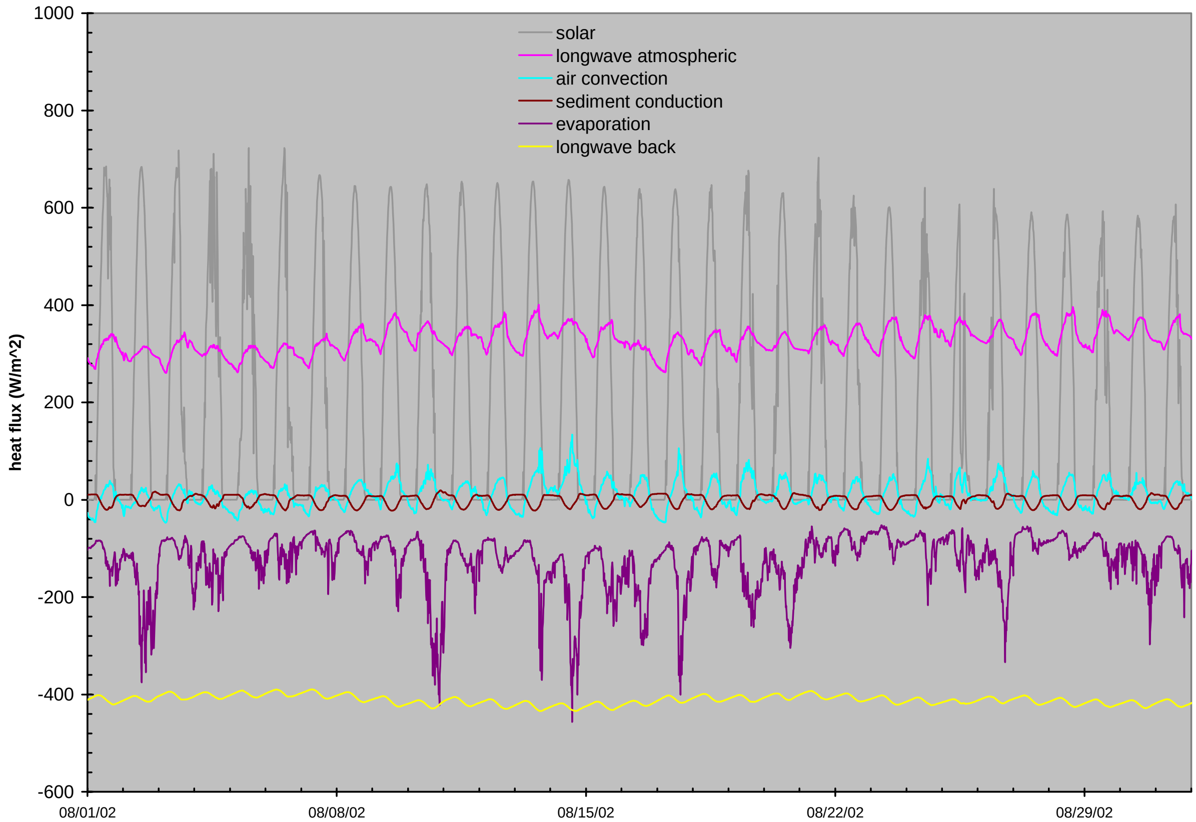



Figure 4. Estimated surface heat fluxes in the Wenatchee River near Monitor during August, 2002. (net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction).

The dominant contribution to the seasonal variations in the equilibrium temperature of water is from seasonal variations in the dew-point temperature (Edinger et al., 1974). The main source of hourly fluctuations in water temperature during the day is solar radiation. Solar radiation generally reaches a maximum during the day when the sun is highest in the sky unless cloud cover or shade from vegetation interferes.

The complete heat budget for a stream also accounts for the mass transfer processes which depend on the amount of flow and the temperature of water flowing into and out of a particular volume of water in a segment of a stream. Mass transfer processes in open channel systems can occur through advection, dispersion, and mixing with tributaries and groundwater inflows and outflows. Mass transfer relates to transport of flow volume downstream, instream mixing, and the introduction or removal of water from a stream. For instance, flow from a tributary will cause a temperature change in the main stem river if the temperature is different in the two water bodies.

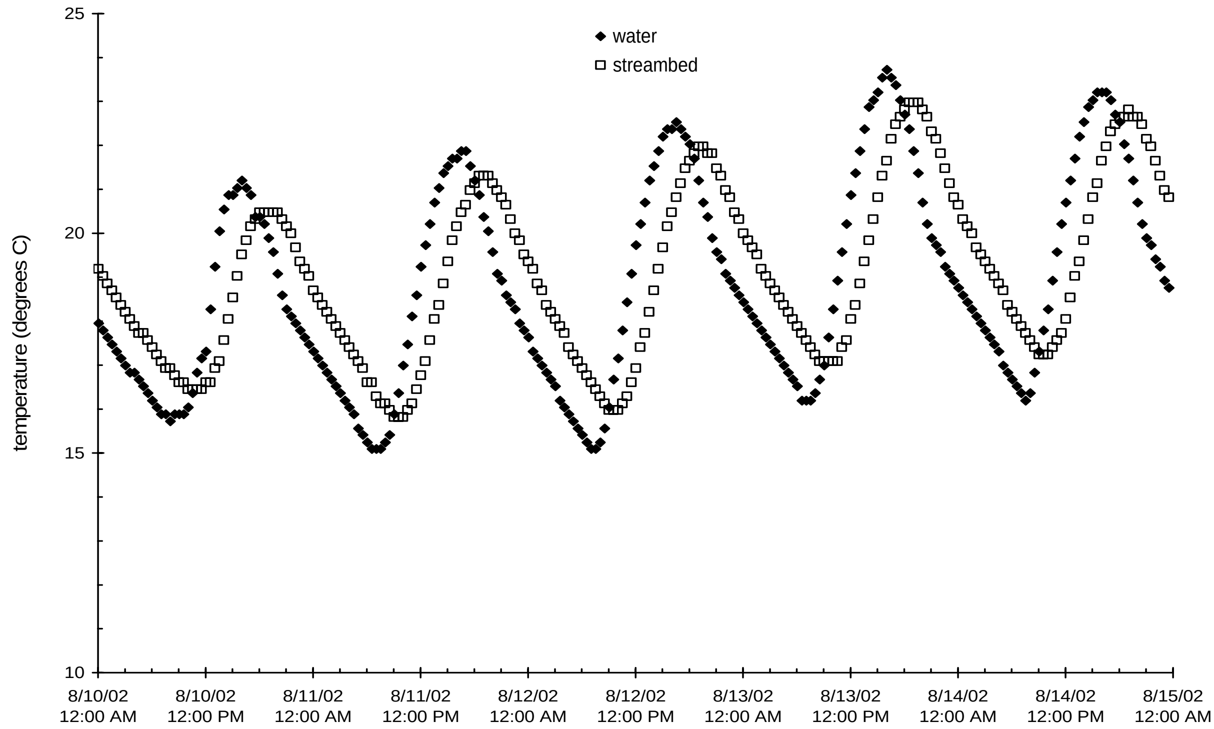



Figure 5. Example of water and streambed temperatures in mid-August. These data are from the North Fork Stillaguamish River and are presented as an example of the type of water and sediment data that have been collected in the Wenatchee basin.

## Thermal role of riparian vegetation

The role of riparian vegetation in maintaining a healthy stream condition and water quality is well documented and accepted in the scientific literature. Summer stream temperature increases due to the removal of riparian vegetation is well documented (*e.g.* Holtby 1988, Lynch et al. 1984, Rishel et al. 1982, Patric 1980, Swift and Messer 1971, Brown et al. 1971, and Levno and Rothacher 1967). These studies generally support the findings of Brown and Krygier (1970) that loss of riparian vegetation results in larger daily temperature variations and elevated monthly and annual temperatures. Adams and Sullivan (1989) also concluded that daily maximum temperatures are strongly influenced by the removal or riparian vegetation because of the effect of diurnal fluctuations in solar heat flux.

Summaries of the scientific literature on the thermal role of riparian vegetation in forested and agricultural areas are provided by Belt et al., 1992, Beschta et al. 1987, Bolton and Monahan 2001, Castelle and Johnson 2000, CH2MHill 2000, GEI 2002, Ice 2001, and Wenger 1999. All of these summaries recognize that the scientific literature indicates that riparian vegetation plays an important role in controlling stream temperature. The list of important benefits that riparian vegetation has upon the stream temperature includes:

- Near stream vegetation height, width and density combine to produce shadows that can reduce solar heat flux to the surface of the water

- Riparian vegetation creates a thermal microclimate that generally maintains cooler air temperatures, higher relative humidity, lower wind speeds, and cooler ground temperatures along stream corridors.
- Near stream vegetation increases bank stability. Channel morphology is often highly influenced by land cover type and condition. Near stream vegetation affects flood plain and instream roughness, contributing coarse woody debris and influencing sedimentation, stream substrate compositions and stream bank stability.

The warming of water temperatures as a stream flows downstream is a natural process. However, the rates of heating can be dramatically reduced when high levels of shade exist and heat flux from solar radiation is minimized. The overriding justification for increases in shade from riparian vegetation is to minimize the contribution of solar heat flux in stream heating. There is a natural maximum level of shade that a given stream is capable of attaining. The importance of shade decreases as the width of a stream increases.

The distinction between reduced heating of streams and actual cooling is important. Shade can significantly reduce the amount of heat flux that enters a stream. Whether there is a reduction in the amount of warming of the stream, maintenance of inflowing temperatures, or cooling of a stream as it flows downstream depends on the balance of all of the heat exchange and mass transfer processes in the stream.

## Effective shade

Shade is an important parameter that controls the stream heating derived from solar radiation. Solar radiation has the potential to be one of the largest heat transfer mechanisms in a stream system. Human activities can degrade near-stream vegetation and/or channel morphology, and in turn, decrease shade. Reductions in shade have the potential to cause significant increases in heat delivery to a stream system. Stream shade may be measured or calculated using a variety of methods (Chen, 1996, Chen et al., 1998, Ice, 2001, OWEB, 1999, Teti, 2001).

Shade is the amount of solar energy that is obscured or reflected by vegetation or topography above a stream. Effective shade is defined as the fraction or percentage of the total possible solar radiation heat energy that is prevented from reaching the surface of the water:

$$\text{effective shade} = (J_1 - J_2)/J_1$$

where $J_1$ is the potential solar heat flux above the influence of riparian vegetation and topography and $J_2$ is the solar heat flux at the stream surface.

In the Northern Hemisphere, the earth tilts on its axis toward the sun during summer months, allowing longer day length and higher solar altitude, both of which are functions of solar declination (i.e., a measure of the earth's tilt toward the sun) (Figure 6). Geographic position (i.e., latitude and longitude) fixes the stream to a position on the globe, while aspect provides the stream/riparian orientation (direction of stream flow). Near-stream vegetation height, width and density describe the physical barriers between the stream and sun that can attenuate and scatter incoming solar radiation (i.e., produce shade) (Table 2). The solar position has a vertical component (i.e., solar altitude) and a horizontal component (i.e., solar azimuth) that are both functions of time/date (i.e., solar declination) and the earth's rotation.

Table 2. Factors that influence stream shade (bold indicates those factors influenced by human activities).

| Description | Parameter |
|---|---|
| Season/time | Date/time |
| Stream characteristics | Aspect, **channel width** |
| Geographic position | Latitude, longitude |
| **Vegetative characteristics** | **Riparian vegetation height, width, and density** |
| Solar position | Solar altitude, solar azimuth |

While the interaction of these shade variables may seem complex, the mathematics that describes them is relatively straightforward geometry. Using solar tables or mathematical simulations, the potential daily solar load can be quantified. The shade from riparian vegetation can be measured with a variety of methods, including (Ice, 2001, OWEB, 1999, Teti, 2001):

- Hemispherical photography
- Angular canopy densiometer
- Solar pathfinder

Hemispherical photography is generally regarded as the most accurate method for measuring shade, although the equipment that is required is significantly more expensive compared with other methods. Angular canopy densiometers (ACD) provide a good balance of cost and accuracy for measuring the importance of riparian vegetation for preventing increases in stream temperature (Teti, 2001, Beschta et al. 1987). Whereas canopy density is usually expressed as a vertical projection of the canopy onto a horizontal surface, the ACD is a projection of the canopy measured at an angle above the horizon at which direct beam solar radiation passes through the canopy. This angle is typically determined by the position of the sun above the horizon during that portion of the day (usually between 10 A.M. and 2 P.M. in mid to late summer) when the potential solar heat flux is most significant. Typical values of the ACD for old-growth stands in western Oregon have been reported to range from 80% to 90%.

Computer programs for the mathematical simulation of shade may also be used to estimate shade from measurements or estimates of the key parameters listed in Table 2 (Ecology 2003a, Chen, 1996, Chen et al., 1998, Boyd, 1996, Boyd and Park, 1998).

## Riparian buffers and effective shade

Trees in riparian areas provide shade to streams and minimize undesirable water temperature changes (Brazier and Brown, 1973; Steinblums et al., 1984). The shading effectiveness of riparian vegetation is correlated to riparian area width (Figure 7). The shade as represented by angular canopy density (ACD) for a given riparian buffer width varies over space and time because of differences among site potential vegetation, forest development stages (e.g., height and density), and stream width. For example, a 50-footwide riparian area with fully developed trees could provide from 45 to 72 percent of the potential shade in the two studies shown in

Figure 7. The Brazier and Brown (1973) shade data show a stronger relationship between ACD and buffer strip width than the Steinblums et al. (1984) data. The $r^2$ correlation for ACD and buffer width was 0.87 and 0.61 in Brazier and Brown (1973) and Steinblums et al. (1984), respectively. This difference supports the use of the Brazier and Brown curve as a basis for measuring shade effectiveness under various riparian buffer proposals. These results reflect the natural variation among old growth sites studied, and show a possible range of potential shade.

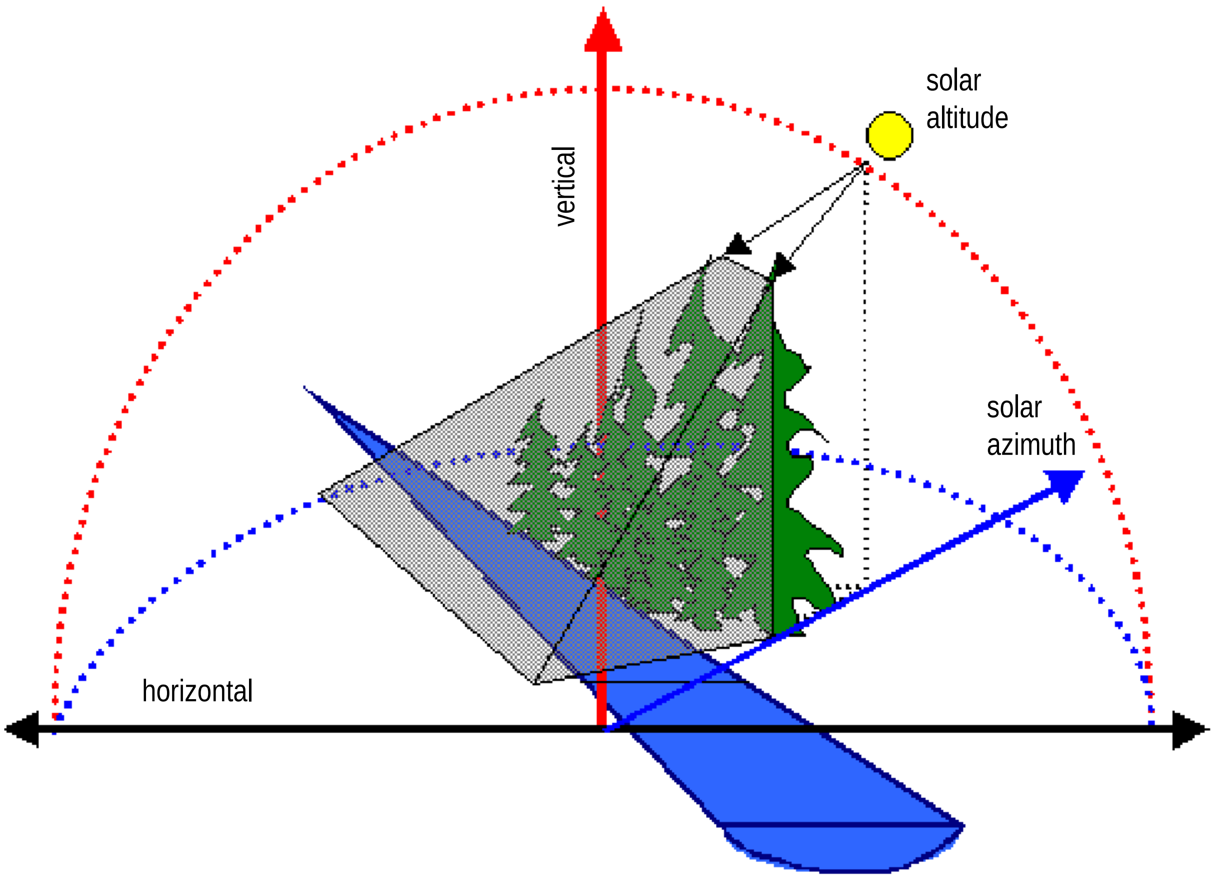



Figure 6. Parameters that affect shade and geometric relationships. Solar altitude is a measure of the vertical angle of the sun's position relative to the horizon. Solar azimuth is a measure of the horizontal angle of the sun's position relative to north.

Several studies of forest streams report that most of the potential shade comes from the riparian area within about 75 feet (23 m) of the channel (CH2MHill 2000, Castelle and Johnson 2000):

- Beschta et al. (1987) report that a 98-foot-wide (30-m) buffer provides the same level of shading as that of an old-growth stand.
- Brazier and Brown (1973) found that a 79-foot (24-m) buffer would provide maximum shade to streams.
- Steinblums et al. (1984) concluded that a 56-foot (17-m) buffer provides 90 percent of the maximum ACD.

- Corbett and Lynch (1985) concluded that a 39-foot (12-m) buffer should adequately protect small streams from large temperature changes following logging.
- Broderson (1973) reported that a 49-foot-wide (15-m) buffer provides 85 percent of the maximum shade for small streams.
- Lynch et al. (1984) found that a 98-foot-wide (30-m) buffer maintains water temperatures within 2°F (1°C) of their former average temperature in small streams (channel width less than 3 m).

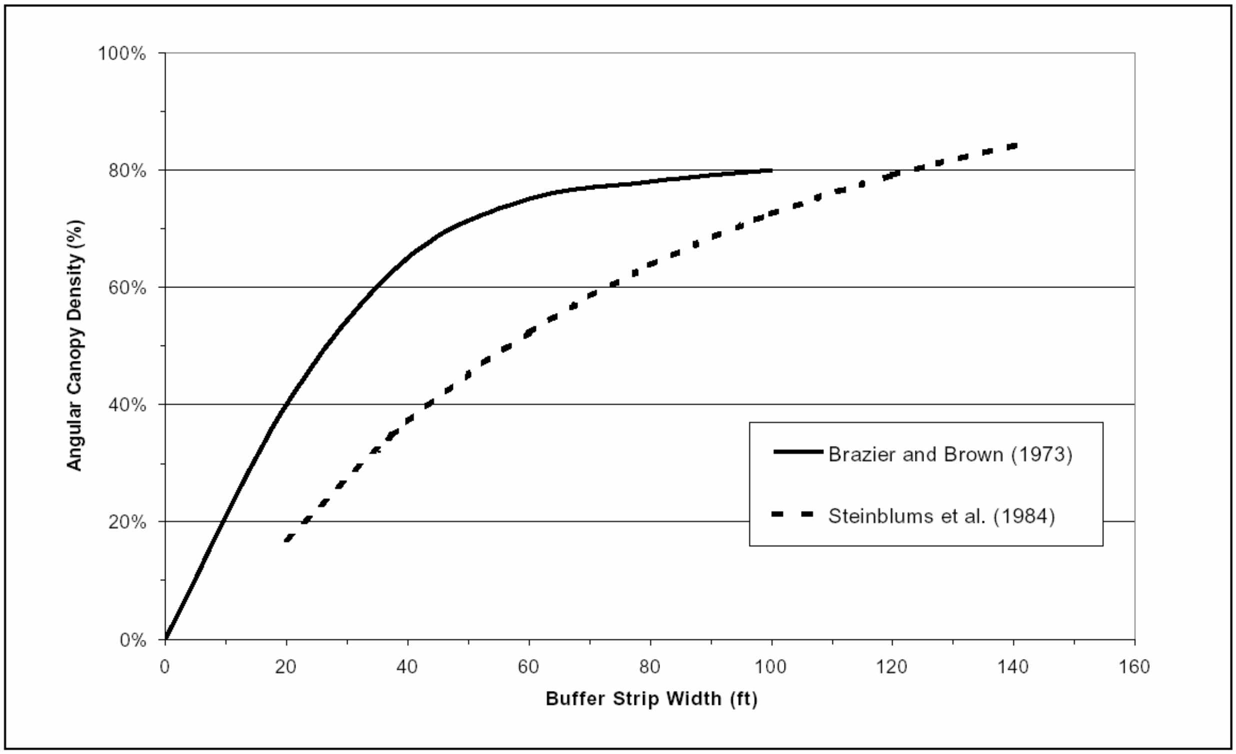



Figure 7. Relationship between angular canopy density and riparian buffer width for small streams in old-growth riparian stands (after Beschta et al., 1987 and CH2MHill, 2000).

GEI (2002) reviewed the scientific literature related to the effectiveness of buffers for shade protection in agricultural areas in Washington and concluded that buffer widths of 10 m (33 feet) provide nearly 80 percent of the maximum potential shade in agricultural areas. Wenger (1999) concluded that a minimum continuous buffer width of 10-30 m should be preserved or restored along each side of all streams on a municipal or county-wide scale to provide stream temperature control and maintain aquatic habitat. GEI (2002) considered the recommendations of Wenger (1999) to be relevant for agricultural areas in Washington.

Steinblums et al. (1984) concluded that that shade could be delivered to forest streams from beyond 75 feet (22 m) and potentially out to 140 feet (43 m). In some site-specific cases, forest practices between 75 and 140 feet from the channel have the potential to reduce shade delivery by up to 25 percent of maximum. However, any reduction in shade beyond 75 feet would probably be relatively low on the horizon, and the impact on stream heating would be relatively low because the potential solar radiation decreases significantly as solar elevation decreases.

## Microclimate - surrounding thermal environment

A secondary consequence of near stream vegetation is its effect on the riparian microclimate. Riparian corridors often produce a microclimate that surrounds the stream where cooler air temperatures, higher relative humidity and lower wind speeds are characteristic. Riparian microclimates tend to moderate daily air temperatures. Relative humidity increases result from the evapotranspiration that is occurring by riparian plant communities. Wind speed is reduced by the physical blockage produced by riparian vegetation.

Riparian buffers commonly occur on both sides of the stream, compounding the edge influence on the microclimate. Brosofske et al. (1997) reported that a buffer width of at least 150 feet (45 m) on each side of the stream was required to maintain a natural riparian microclimate environment in small forest streams (channel width less than 4 m) in the foothills of the western slope of the Cascade mountains in western Washington with predominantly Douglas-fir and western hemlock.

Bartholow (2000) provided a thorough summary of literature of documented changes to the environment of streams and watersheds associated with extensive forest clearing. Changes summarized by Bartholow (2000) are representative of hot summer days and indicate the mean daily effect unless otherwise indicated:

- **Air temperature**. Edgerton and McConnell (1976) showed that removing all or a portion of the tree canopy resulted in cooler terrestrial air temperatures at night and warmer temperatures during the day, enough to influence thermal cover sought by elk (Cervus canadensis) on their eastern Oregon summer range. Increases in maximum air temperature varied from 5 to 7 degrees C for the hottest days (estimate). However, the mean daily air temperature did not appear to have changed substantially since the maximum temperatures were offset by almost equal changes to the minima. Similar temperatures have been commonly reported (Childs and Flint, 1987; Fowler et al., 1987), even with extensive clearcuts (Holtby, 1988). In an evaluation of buffer strip width, Brosofske et al. (1997) found that air temperatures immediately adjacent to the ground increased 4.5 degrees C during the day and about 0.5 degrees C at night (estimate). Fowler and Anderson (1987) measured a 0.9 degrees C air temperature increase in clearcut areas, but temperatures were also 3 degrees C higher in the adjacent forest. Chen et al. (1993) found similar (2.1 degrees C) increases. All measurements reported here were made over land instead of water, but in aggregate support about a 2 degrees C increase in ambient mean daily air temperature resulting from extensive clearcutting.
- **Relative humidity**. Brosofske et al. (1997) examined changes in relative humidity within 17 to 72 m buffer strips. The focus of their study was to document changes along the gradient from forested to clearcut areas, so they did not explicitly report pre- to post-harvest changes at the stream. However, there appeared to be a reduction in relative humidity at the stream of 7% during the day and 6% at night (estimate). Relative humidity at stream sites increased

exponentially with buffer width. Similarly, a study by Chen et al. (1993) showed a decrease of about 11% in mean daily relative humidity on clear days at the edges of clearcuts.

- **Wind speed**. Brosofske et al. (1997) reported almost no change in wind speed at stream locations within buffer strips adjacent to clearcuts. Speeds quickly approached upland conditions toward the edges of the buffers, with an indication that wind actually increased substantially at distances of about 15 m from the edge of the strip, and then declined farther upslope to pre-harvest conditions. Chen et al. (1993) documented increases in both peak and steady winds in clearcut areas; increments ranged from 0.7 to 1.2 m/s (estimated).

Spence et al. (1996) also provided a summary of literature related to the influence of riparian vegetation on microclimate as follows:

- Chen (1991) reported that soil and air temperatures, relative wind speed, humidity, soil moisture, and solar radiation all changed with increasing distance from the edges of clearcuts in the western Cascades.
- FEMAT (1993) concluded from Chen's work that the loss of upland forests probably influences conditions within the riparian zone. FEMAT also suggested that riparian buffers for maintaining microclimates need to be wider than those for protecting other riparian functions.

## Thermal role of channel morphology

Changes in channel morphology, namely channel widening, affects stream temperatures. As a stream widens, the surface area exposed to heat flux increases, resulting in increased energy exchange between a stream and its environment (Chapra, 1997). Further, wide channels are likely to have decreased levels of shade due to the increased distance created between vegetation and the wetted channel and the decreased fraction of the stream width that could potentially be covered by shadows from riparian vegetation. Conversely, narrow channels are more likely to experience higher levels of shade.

Channel widening is often related to degraded riparian conditions that allow increased stream bank erosion and sedimentation of the streambed, both of which correlate strongly with riparian vegetation type and condition (Rosgen 1996). Channel morphology is not solely dependent on riparian conditions. Sedimentation can deposit material in the channel, fill pools and agrade the streambed, reducing channel depth and increasing channel width.

Channel modification usually occurs during high flow events. Land uses that affect the magnitude and timing of high flow events may negatively impact channel width and depth. Riparian vegetation conditions will affect the resilience of the stream banks/flood plain during periods of sediment introduction and high flow. Disturbance processes may have differing results depending on the ability of riparian vegetation to shape and protect channels. Channel morphology is related to riparian vegetation composition and condition by:

- **Building stream banks**. Trap suspended sediments, encourage deposition of sediment in the flood plain and reduce incoming sources of sediment.
- **Maintaining stable stream banks**. High rooting strength and high stream bank and flood plain roughness prevent stream bank erosion.

- **Reducing flow velocity** (erosive kinetic energy). Supplying large woody debris to the active channel, high pool:riffle ratios and adding channel complexity that reduces shear stress exposure to stream bank soil particles.

## Pollutant sources

Anthropogenic heat sources are derived from solar radiation as increased levels of solar radiation reach the stream surface, effluent discharges to surface waters, and flow augmentation. The pollutants targeted in this TMDL are heat from human caused increases in solar radiation loading to the stream network, and heat from warm water discharges of human origin.

Riparian vegetation, stream morphology, hydrology, climate, and geographic location influence stream temperature. While climate and geographic location are outside of human control, riparian condition, channel morphology and hydrology are affected by land use activities.

Low summertime flows decrease the thermal assimilative capacity of streams. Pollutant loading causes larger temperature increases in stream segments where flows are reduced.

Heat loading from point sources occurs when waters with differing temperatures are mixed. Waste load allocations are developed for point sources that discharge to temperature impaired waterbodies or discharge into waterbodies that drain to temperature impaired waterbodies.

## Pollutants and surrogate measures

Heat loads to the stream are calculated in this TMDL in units of calories per square centimeter per day or watts per square meter ($W/m^2$). However, heat loads are of limited value in guiding management activities needed to solve identified water quality problems.

The Wenatchee River temperature TMDL will incorporate measures other than “daily loads” to fulfill the requirements of Section 303(d). This TMDL allocates other appropriate measures, or “surrogate measures” as provided under EPA regulations [40 CFR 130.2(i)]. The “Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program” (EPA, 1998) includes the following guidance on the use of surrogate measures for TMDL development:

> “When the impairment is tied to a pollutant for which a numeric criterion is not possible, or where the impairment is identified but cannot be attributed to a single traditional “pollutant,” the state should try to identify another (surrogate) environmental indicator that can be used to develop a quantified TMDL, using numeric analytical techniques where they are available, and best professional judgment (BPJ) where they are not.”

Water temperature increases as a result of increased heat flux loads. A loading capacity for radiant heat energy (e.g., incoming solar radiation) can be used to define a reduction target that forms the basis for identifying a surrogate for heat loading from solar radiation. This technical assessment for the Wenatchee River temperature TMDL uses effective shade as a surrogate measure of heat flux from solar radiation to fulfill the requirements of Section 303(d). Effective shade is defined as the fraction of the potential solar shortwave radiation that is blocked by vegetation and topography before it reaches the stream surface. The definition of effective shade allows direct translation of the solar radiation loading capacity.

Because factors that affect water temperature are interrelated, the surrogate measure (effective shade) relies on restoring/protecting riparian vegetation to increase stream surface shade levels, reducing stream bank erosion, stabilizing channels, reducing the near-stream disturbance zone width and reducing the surface area of the stream exposed to radiant processes. Effective shade screens the water's surface from direct rays of the sun. Other factors influencing heat flux and water temperature were also considered, including microclimate, channel geometry, groundwater recharge, and instream flow.

# Background

The Wenatchee River Subbasin (WRIA 45) encompasses 878,423 acres and is located in the central part of Washington State. The subbasin is bounded on the west by the Cascade Mountians, on the north and east by the Entiat Mountains, and on the south by the Wenatchee Mountains. The Wenatchee is a subbasin to the Columbia River and enters that system at the city of Wenatchee 15 miles upstream of the Rock Island Dam. The geology of the upper subbasin consists of high and low relief landtypes associated with glaciation (e.g. cirque headwalls, glaciated ridges, and glacial/fluvial outwash). The middle part of the subbasin is a mixture of igneous and basalt rock formations and glacial/fluvial outwash terraces. Alluvial fans and terraces are predominant landtypes in the lower Wenatchee (Mainstem Wenatchee Watershed Assessment, 1999).

Annual average precipitation throughout the subbasin ranges from 150 inches at the crest of the Cascades to 8.5 inches in Wenatchee (Mainstem Wenatchee Watershed Assessment, 1999; Figure 8). Streamflow varies during the year, but mean monthly discharge peaks in spring from combined effects of snowmelt and rain on snow events. Most of the annual stream flow in the Wenatchee River originates from tributaries in the upper subbasin: the White River (25%), Icicle Creek (20%), Nason Creek (18%), the Chiwawa River (15%), and the Little Wenatchee River (15%) (Andonaegui, 2001). Both the White and the Little Wenatchee Rivers enter Lake Wenatchee in the upper subbasin; the mouth of the lake is the head of the Wenatchee River and Nason Creek enters the river just below the lake outlet. Land cover in the Wenatchee River watershed is shown in Table 3 (USGS, 1999).

Table 3. Land cover in the Wenatchee River watershed.

| | Area Km^2 | percent of total |
|---|---|---|
| Water | 52.29 | 1.5% |
| Developed | 15.03 | 0.4% |
| Barren | 245.77 | 7.1% |
| forrested upland | 2409.44 | 69.4% |
| Shrubland | 281.13 | 8.1% |
| orchard/vineyard/other non-natural woody | 48.74 | 1.4% |
| herbaceous upland | 409.42 | 11.8% |
| herbaceous planted/cultivated | 5.16 | 0.1% |
| Wetlands | 6.02 | 0.2% |
| Total | 3473.00 | |

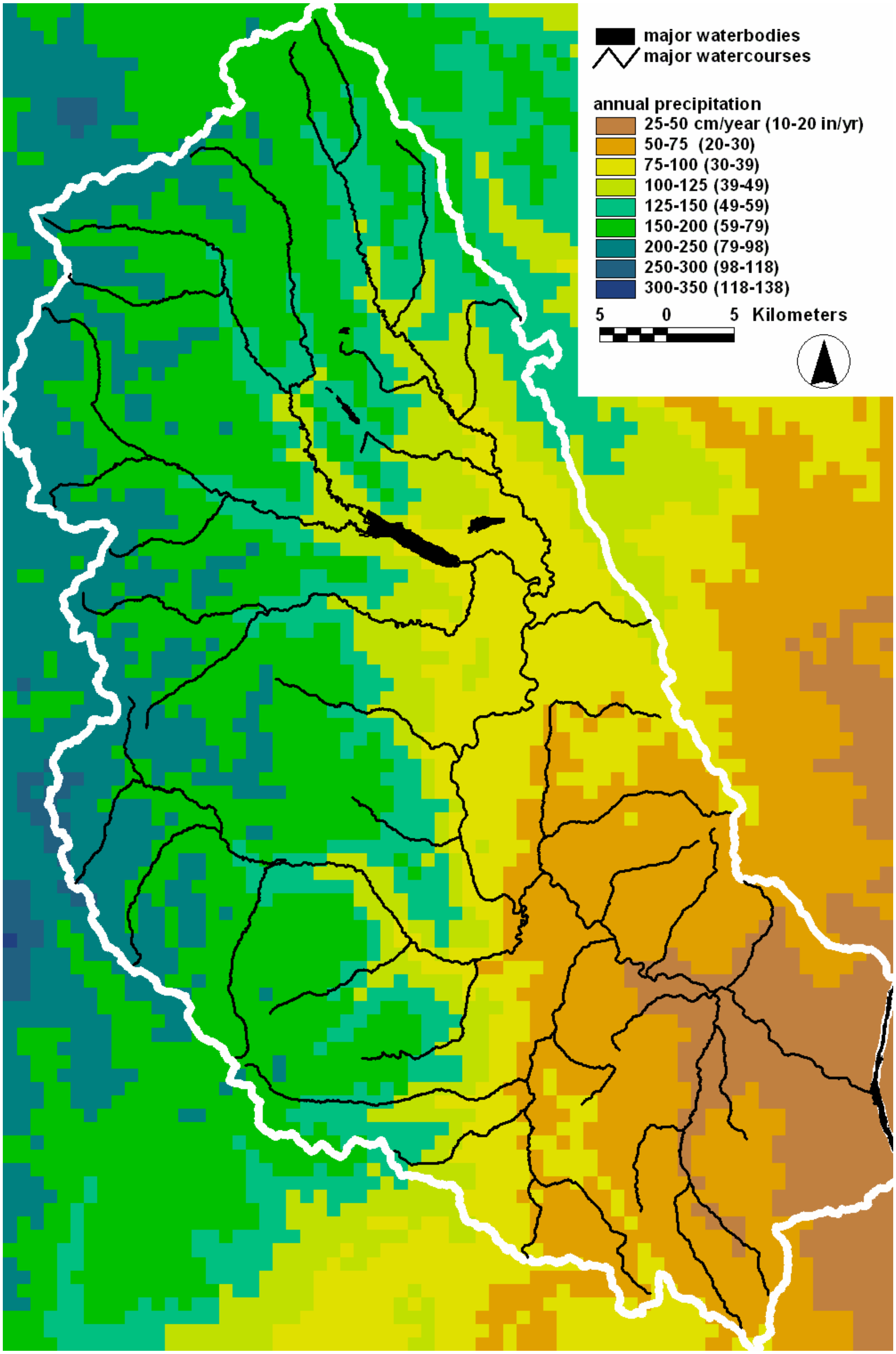



Figure 8. Annual average precipitation in the Wenatchee River watershed (data from www.daymet.org).

## Land ownership

There is a mixture of federal, state, county, and private land ownership throughout the subbasin. Most of the upper subbasin is designated federal wilderness area and is under the jurisdiction of the U.S. Forest Service Lake Wenatchee and Leavenworth Ranger Districts. State Highways 2 and 97 parallel much of the Wenatchee mainstem and Nason Creek and contain portions of their streambanks. The incorporated cities designated in the 2000 census are Wenatchee (population 27,856), Cashmere (population 2,965), and Leavenworth (population 2,074). There are smaller unincorporated towns and communities located along State Highways 2 and 97 (2000 census information).

## Forest land cover

Most of the land area in the Wenatchee River watershed is covered with forest (Table 3). Federally owned forest land is managed according to the USFS Forest Plan. A technical report that was published by Ecology in 2003 presents the TMDL for water temperature and the Load Allocations that are required on forest land that owned and managed by the USFS in the Wenatchee National Forest (Whiley and Cleland, 2003).

Forest land in the watershed that is not owned and managed by the USFS is subject to the Washington State DNR Forest and Fish Report.

### USFS Forest Plan

Forest plans are required by the National Forest Management Act (NFMA) for each National Forest. These plans establish land allocations, goals and objectives, and standards and guidelines that direct how National Forest System lands are managed.

The Aquatic Conservation Strategy, a component of the amended forest plan, is designed to protect and restore the ecological health of the aquatic system and its dependent species. Restoration priorities are based on watershed analysis and planning which will help to determine areas where the greatest benefits can be achieved along with the likelihood of success. In general, watersheds that currently have the best habitat, or those with the greatest potential for recovery, are priority areas for increased protection and for restoration treatments. The conservation strategy aims to maintain the natural disturbance regime. Components of the Aquatic Conservation Strategy include:

- Riparian Reserves: Lands along streams, wetlands, ponds, lakes, and unstable and potentially unstable areas where special standards and guidelines direct land use. Riparian reserves are designed to maintain and restore the ecological health of watersheds and aquatic ecosystems. Interim widths for Riparian Reserves are established based on ecological, hydrologic, and geomorphic factors. Interim Riparian Reserves for federal lands are delineated as part of the watershed analysis process based on identification and evaluation of critical hillslope, riparian, and channel processes. Final Riparian Reserve boundaries are determined at the site-specific level during the appropriate National Environmental Policy Act analysis.

- Key Watersheds: A system of refugia comprising watersheds crucial to at-risk fish species and stocks while also providing high quality habitat. Key Watersheds are generally those identified as having the best habitat or those with the greatest potential for recovery. Key watersheds are priority areas for increased protection and for restoration treatments. Activities to protect and restore aquatic habitat in Key Watersheds are a higher priority than similar activities in other watersheds.
- Watershed Analysis: An on-going, iterative analysis procedure for characterizing watershed and ecological processes to meet specific management objectives within the subject watershed. This analysis should enable watershed planning that achieves Aquatic Conservation Strategy objectives. Watershed analysis provides the basis for monitoring and restoration programs and the foundation from which the Riparian Reserves can be delineated.
- Watershed Restoration: A comprehensive, long-term program of watershed restoration to restore watershed health and aquatic ecosystems, including habitats supporting fish and other aquatic and riparian-dependent organisms.

Riparian Reserves are specified for categories of streams or water bodies as follows:

- Fish-bearing streams - Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of two site-potential trees, or 300 feet slope distance (600 feet total, including both sides of the stream channel), whichever is greatest.
- Permanently flowing non-fish bearing streams - Riparian Reserves consist of the stream and the area on each side of the stream extending from the edges of the active stream channel to the top of the inner gorge, or to the outer edges of the 100-year flood plain, or to the outer edges of riparian vegetation, or to a slope distance equal to the height of one site-potential tree, or 150 feet slope distance (300 feet total, including both sides of the stream channel), whichever is greatest.
- Specific riparian reserves ranging from 100 to 300 feet of slope distance are also specified for the following categories of riparian areas: constructed ponds and reservoirs; wetlands (greater than one acre), lakes, and natural ponds; seasonally flowing or intermittent streams; wetlands less than one acre, and unstable and potentially unstable areas.

Additional measures are being undertaken within the Wenatchee Forest through a roads analysis. The objective of the roads analysis is to provide critical information needed to identify and manage a minimum road system that is safe and responsive to public needs while having minimal adverse effects on ecological processes and health. This planning action is being accomplished with public and agency (federal and state) input.

Water Quality Restoration Plans are Forest Service planning documents that identify Best Management Practice actions appropriate to correct water quality issues within defined drainage areas. These plans will enhance and focus activities and improve shade levels in areas where the plans are developed.

Ecology staff are involved in review of USFS planning and implementation activities to ensure that state water quality laws and regulations are being met or exceeded. This includes the responsibility to certify that general water quality Best Management Practices (BMPs) and current Forest Plans are consistent with the CWA. The certification process includes the comparison of state BMPs and USFS BMPs. If Ecology or the USFS determines that USFS BMPs provide less resource protection than state BMPs, the USFS will review the BMPs for amendment.

## TFW and the Forests and Fish Report

In 1986, as an alternative to competitive lobbying and court cases, four caucuses (the Tribes, the timber industry, the state, and the environmental community) decided to try to resolve contentious forest practices problems on non-federal land through negotiations. This resulted in the first Timber Fish Wildlife (TFW) agreement in February 1987. Subsequent events caused the TFW caucuses to again come together at the policy level to address a new round of issues. Under the Endangered Species Act, several salmonid populations have been listed or considered for listing. In addition, over 660 Washington streams have been included on a 303(d) list identifying stream segments with water quality problems under the Clean Water Act.

In November 1996, the caucuses - now expanded from the original four to six with the addition of federal and local governments - decided to work together to develop joint solutions to these problems. The Forests and Fish Report was presented to the Forest Practices Board of the state Department of Natural Resources and the Governor's Salmon Recovery Office in February, 1999 (www.wa.gov/dnr/htdocs/fp/fpb/forests&fish.html). The goals of the forestry module of the Forests and Fish Report are fourfold:

- Provide compliance with the Endangered Species Act for aquatic and riparian-dependent species on non-federal forest lands
- Restore and maintain riparian habitat on non-federal forest lands to support a harvestable supply of fish
- Meet the requirements of the Clean Water Act for water quality on non-federal forest lands
- Keep the timber industry economically viable in the State of Washington.

To achieve the overall objectives of the Forests and Fish initiative, significant changes in current riparian forest management policy are prescribed. The goal of riparian management and conservation as recommended in the Forests and Fish report is to achieve restoration of high levels of riparian function and maintenance of these levels once achieved.

Desired future conditions are the stand conditions of a mature riparian forest, agreed to be 140 years of age (the midpoint between 80 and 200 years) and the attainment of resource objectives. For Eastside forests such as the forest land in the Wenatchee River watershed, riparian management is intended to provide stand conditions that vary over time within a range that meets functional conditions and maintains general forest health. These desired future conditions are a reference point on the pathway to restoration of riparian functions, not an endpoint of riparian stand development.

The riparian functions addressed by the recommendations in the Forests and Fish report include bank stability, the recruitment of woody debris, leaf litter fall, nutrients, sediment filtering, shade, and other riparian features that are important to both riparian forest and aquatic system conditions. The diversity of riparian forests across the landscapes is addressed by tailoring riparian prescriptions to the site productivity and tree community at specific sites.

Load allocations are included in a TMDL for forest lands in the Wenatchee River Basin will be proposed in accordance with the section of Forests and Fish entitled "TMDLs produced prior to 2009 in mixed use watersheds". Also consistent with the Forests and Fish agreement, implementation of the load allocations established in this TMDL for private and state forestlands will be accomplished via implementation of the revised forest practice regulations. The effectiveness of the Forests and Fish rules will be measured through the adaptive management process and monitoring of streams in the watershed. If shade is not moving on a path toward the TMDL load allocation by 2009, Ecology will suggest changes to the Forest Practices Board.

Washington State Department of Natural Resources (DNR) is encouraged to condition forest practices to prohibit any further reduction of stream shade and not waive or modify any shade requirements for timber harvesting activities on state and private lands. Ecology is committed in assisting DNR in identifying those site-specific situations where reduction of shade has the potential for or could cause material damage to public resources.

New emergency rules for roads also apply. These include new road construction standards, as well as new standards and a schedule for upgrading existing roads. Under the new rules, roads must provide for better control of road-related sediments, provide better streambank stability protection, and meet current Best Management Practices. DNR is also responsible for oversight of these activities.

The Department of Ecology policy for considering the Forest and Fish Report in temperature TMDLs is as follows. Load allocations in the technical report are generally established in accordance with Schedule M-2 of the Forests and Fish Report, February 1999 (www.wa.gov/dnr/htdocs/fp/fpb/forests&fish.html). Also consistent with the Forests and Fish agreement, implementation of the load allocations for private and state forest lands are generally accomplished via implementation of the revised forest practice regulations. The effectiveness of the Forests and Fish rules are generally measured through the adaptive management processes and monitoring of streams in the watershed. If shade is not moving on a path toward the TMDL load allocation by 2009, Ecology's policy is to suggest changes to the Forest Practices Board.

## Other regulations affecting riparian land use

For private land that is neither federal forest nor covered by the Forests and Fish Report (i.e., private and state-owned forest), some regulations affect land use and management along rivers and streams:

- Shorelines of rivers with annual flows greater than 1,000 cfs and streams with average flows greater than 20 cfs are managed under the Shoreline Management Act;

- Within municipal boundaries, land management practices next to streams may be limited if there is a local critical areas ordinance;
- Outside municipalities, county sensitive areas ordinances may affect such practices as grading or clearing next to a stream, if the activity comes under county review as part of a permit application.

## Instream flow rule for the Wenatchee River

Instream flows and water withdrawals are managed through regulatory avenues separate from TMDLs. However, stream temperature is related to the amount of instream flow, and increases in flow generally result in decreases in maximum temperatures. The complete heat budget for a stream segment accounts for the amount of flow and the temperature of water flowing into and out of the stream.

The primary statutes relating to flow setting in the State of Washington are as follows:

- Water Code, Chapter 90.03 RCW (1917), in section 247, describes Ecology's exclusive authority for setting flows and describes specific conditions on permits stating where flows must be met. It requires consultation with the Department of Fish and Wildlife, the Department of Community, Trade, and Economic Development, the Department of Agriculture as well as affected Indian Tribes on the establishment of "minimum flows".
- Construction Projects in State Waters, Chapter 77.55 RCW (formerly 75.20)(1949), section 050, requires Ecology to consult with the Department of Fish and Wildlife prior to making a decision on any water right application that may affect flows for food and game fish. Fish and Wildlife may recommend denial or conditioning of a water right permit.
- Minimum Water Flows and Levels Act, Chapter 90.22 RCW (1967), sets forth a process for protecting instream flows through adoption of rules. Among other provisions, it says Ecology must consult with the Department of Fish and Wildlife and conduct public hearings.
- Water Resources Act of 1971, Chapter 90.54 RCW, particularly section 020, includes language that says "base flows" are to be retained in streams except where there are "overriding considerations of the public interest". Further, waters of the state are to be protected and utilized for the greatest benefit to the people, and water allocation is to be generally based on the securing of "maximum net benefits" to the people of the state. This Act also authorizes Ecology to reserve waters for future beneficial uses.
- In 1998, the legislature passed Engrossed Substitute House Bill 2514, which was codified as "Watershed Planning," Chapter 90.82 RCW. This chapter provides an avenue for local citizens and various levels of governments to be involved in collaborative water management, including the option of establishing or amending instream flow rules. The Watershed Planning process specifies that local watershed planning groups can recommend instream flows to Ecology for rule-making, and directs Ecology to undertake rule making to adopt flows upon receiving such a recommendation.

Under state laws, the Washington Department of Ecology oversees both the appropriation of water for out-of-stream uses (e.g. irrigation, municipalities, commercial and industrial uses) and the protection of instream uses (e.g. water for fish habitat and recreational use). Ecology does this by adopting and enforcing regulations, as well as by providing assistance to citizens regarding both public and private water management issues.

Ecology is required by law to protect instream flows by adopting regulations and to manage water uses that affect stream flow. To develop an "instream flow rule" which sets for a particular stream the minimum flows needed during critical times of year, Ecology considers existing flow data, the hydrology of a stream and its natural seasonal flow variation, fish habitat needs, and other factors. Once adopted, an instream flow rule acquires a priority date similar to that associated with a water right. Water rights existing at the time an instream flow rule is adopted are unaffected by the rule and those issued after rule adoption are subject to the requirements of the rule.

# Applicable Water Quality Criteria

## Current water quality criteria

This report and the subsequent TMDL are designed to address impairments of characteristic uses caused by high temperatures. The characteristic uses designated for protection in Wenatchee River basin streams are as follows (Chapter 173-201A WAC):

> "Characteristic uses. Characteristic uses shall include, but not be limited to, the following:
> (i) Water supply (domestic, industrial, agricultural).
> (ii) Stock watering.
> (iii) Fish and shellfish:
> Salmonid migration, rearing, spawning, and harvesting.
> Other fish migration, rearing, spawning, and harvesting.
> Clam and mussel rearing, spawning, and harvesting.
> Crayfish rearing, spawning, and harvesting.
> (iv) Wildlife habitat.
> (v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).
> (vi) Commerce and navigation."

The characteristics uses that are of the most concern in this TMDL are salmonid and other fish migration, rearing, spawning, and harvesting.

The state water quality standards describe criteria for temperature for the protection of characteristic uses. Streams in the Wenatchee River basin are designated as either Class AA or Class A. The definitions of class AA and A are as follows:

- Class AA waters typically exhibit extraordinary water quality that markedly and uniformly exceeds the requirements for all or substantially all uses.
- Class A waters typically exhibit excellent water quality that meets or exceeds the requirements for all or substantially all uses.

The temperature criteria for Class AA waters are as follows:

> "Temperature shall not exceed 16.0°C…due to human activities. When natural conditions exceed 16.0°C…, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

The temperature criteria for Class A waters are as follows:

> "Temperature shall not exceed 18.0°C…due to human activities. When natural conditions exceed 18.0°C…, no temperature increases will be allowed which will raise the receiving water temperature by greater than 0.3°C."

During critical periods, natural conditions may exceed the numeric temperature criteria mandated by the water quality standards. In these cases, the antidegradation provisions of those standards apply.

> "Whenever the natural conditions of said waters are of a lower quality than the criteria assigned, the natural conditions shall constitute the water quality criteria."

## 2003 revised water quality criteria

Ecology is in the process of changing the water quality criteria for temperature. The TMDL will be written to meet the water quality criteria that are in effect at the time the final document is published (or submitted to EPA for approval). The proposed revised 2003 criteria for temperature are described in the following excerpt from the criteria document:

> (c) **Aquatic life temperature criteria.** Except where noted, water temperature is measured by the 7-day average of the daily maximum temperatures (7-DADMax). Table 200 (1)(c) lists the temperature criteria for each of the aquatic life use categories.

**Table 200 (1)(c)**
**Aquatic Life Temperature Criteria in Fresh Water (*note: only categories applicable in WRIA 45 are shown*)**

| **Category** | **Highest 7-DADMax** |
|---|---|
| Char | 12°C (53.6°F) |
| Salmon and Trout Spawning, **Core** Rearing, and Migration | 16°C (60.8°F) |
| Salmon and Trout Spawning, **Noncore** Rearing, and Migration | 17.5°C (63.5°F) |

(i) When a water body's temperature is warmer than the criteria in Table 200 (1)(c) (or within 0.3°C (0.54°F) of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).
(ii) When the natural condition of the water is cooler than the criteria in Table 200 (1)(c), the allowable rate of warming up to, but not exceeding, the numeric criteria from human actions is restricted as follows:
(A) Incremental temperature increases resulting from individual point source activities must not, at any time, exceed 28/(T+5) as measured at the edge of a mixing zone

boundary (where "T" represents the background temperature as measured at a point or points unaffected by the discharge and representative of the highest ambient water temperature in the vicinity of the discharge); and
(B) Incremental temperature increases resulting from the combined effect of all nonpoint source activities in the water body must not, at any time, exceed 2.8°C (5.04°F).
(iii) Temperatures are not to exceed the criteria at a probability frequency of more than once every ten years on average.
(iv) Spawning and incubation protection. Where the department determines the temperature criteria established for a water body would likely not result in protective spawning and incubation temperatures, the following criteria apply:
• Maximum 7-DADMax temperatures of 9°C (48.2°F) at the initiation of spawning and at fry emergence for char; and
• Maximum 7-DADMax temperatures of 13°C (55.4°F) at the initiation of spawning for salmon and at fry emergence for salmon and trout.
The two criteria above are protective of incubation as long as human actions do not significantly disrupt the normal patterns of fall cooling and spring warming that provide significantly colder temperatures over the majority of the incubation period. The department will maintain a list of waters where the single-summer maximum criterion is not sufficient to protect spawning and incubation.
(v) For lakes, human actions considered cumulatively may not increase the 7-DADMax temperature more than 0.3°C (0.54°F) above natural conditions.
(vi) Temperature measurements should be taken to represent the dominant aquatic habitat of the monitoring site. This typically means samples should:
(A) Be taken from well mixed portions of rivers and streams; and
(B) Not be taken from shallow stagnant backwater areas, within isolated thermal refuges, at the surface, or at the water's edge.
(vii) The department will incorporate the following guidelines on preventing acute lethality and barriers to migration of salmonids into determinations of compliance with the narrative requirements for use protection established in this chapter (e.g., WAC 173-201A-310(1), 173-201A-400(4), and 173-201A-410 (1)(c)). The following site-level considerations do not, however, override the temperature criteria established for waters in subsection (1)(c) of this section or WAC 173-201A-602:
(A) Moderately acclimated (16-20°C, or 60.8.68°F) adult and juvenile salmonids will generally be protected from acute lethality by discrete human actions maintaining the 7-DADMax temperature at or below 22°C (71.6°F) and the 1-day maximum (1-DMax) temperature at or below 23°C (73.4°F).
(B) Lethality to developing fish embryos can be expected to occur at a 1-DMax temperature greater than 17.5°C (63.5°F).
(C) To protect aquatic organisms, discharge plume temperatures must be maintained such that fish could not be entrained (based on plume time of travel) for more than two seconds at temperatures above 33°C (91.4°F) to avoid creating areas that will cause near instantaneous lethality.
(D) Barriers to adult salmonid migration are assumed to exist any time the 1-DMax temperature is greater than 22°C (71.6°F) and the adjacent downstream water temperatures are 3°C (5.4°F) or more cooler.
(viii) Nothing in this chapter shall be interpreted to prohibit the establishment of effluent limitations for the control of the thermal component of any discharge in accordance with 33 U.S.C. 1326 (commonly known as section 316 of the Clean Water Act).

All streams and rivers in the study area that are class AA under the current criteria will be designated “core” under the 2003 revised criteria [see Table 200(1)(c) above], and class A will be designated “non-core” except for the specific designations listed in Appendix A..

# Seasonal variation

Clean Water Act (CWA) Section 303(d)(1) requires that TMDLs "be established at the level necessary to implement the applicable water quality standards with seasonal variations". The current regulation also states that determination of "TMDLs shall take into account critical conditions for stream flow, loading, and water quality parameters" [40 CFR 130.7(c)(1)]. Finally, Section 303(d)(1)(D) suggests consideration of normal conditions, flows, and dissipative capacity.

Existing conditions for stream temperatures in the Wenatchee River watershed reflect seasonal variation. Cooler temperatures occur in the winter, while warmer temperatures are observed in the summer. The highest temperatures typically occur from mid-July through mid-August. This time frame is used as the critical period for development of the TMDL.

Seasonal estimates for stream flow, solar flux, and climatic variables for the TMDL are taken into account to develop critical conditions for the TMDL model. The critical period for evaluation of solar flux and effective shade will be assumed to be August 1 because it is the mid-point of the period when water temperatures are typically at their seasonal peak.

Critical stream flows for the TMDL will be evaluated as the lowest 7-day average flows with a 2-year recurrence interval (7Q2) and 10-year recurrence interval (7Q10) for the months of July and August. The 7Q2 stream flow will be assumed to represent conditions that would occur during a typical climatic year, and the 7Q10 stream flow was assumed to represent a reasonable worst-case climatic year.

# Technical analysis

## Stream heating processes

Riparian vegetation, stream morphology, hydrology, climate, and geographic location influence stream temperature. While climate and geographic location are outside of human control, riparian condition, channel morphology and hydrology are affected by land use activities. Specifically, the elevated summertime stream temperatures attributed to anthropogenic sources in the Wenatchee River basin result from the following:

- Riparian vegetation disturbance reduces stream surface shading via decreased riparian vegetation height, width, and/or density, thus increasing the amount of solar radiation reaching the stream surface.
- Channel widening reduces the stream depth and increases the stream surface area exposed to energy processes, namely solar radiation.
- Reduced summertime base flows may result from instream withdrawals and hydraulically connected groundwater withdrawals. Reducing the amount of water in a stream can increase stream temperature (Brown, 1972). Base flows could also have been reduced due to an increase in impervious surface area from changes in land cover in the watershed.

# Current conditions

## Meteorology

Regional air temperature, dewpoint temperature, and solar radiation during July-September 2002 are shown in Figure 9. Highest daily average stream temperatures occurred during the period of relatively high air temperatures in mid August.

## Water temperature data – continuous dataloggers

A network of continuous temperature dataloggers was installed in the Wenatchee River watershed by the Department of Ecology as described by Bilhimer et al., 2002. A narrative description of each of the datalogger stations and a summary of data quality is provided in Appendix B. Data from 2002 show that water temperatures in excess of the current class A or AA standards and proposed core/non-core standards are common throughout the watershed (Table 4).

Figure 10 summarizes the highest daily maximum and the highest seven-day average maximum water temperatures of each year for 2002. Figures 11-13 present continuous daily maximum water temperatures during July-September at each of the sampling locations during 2002.

## Water temperature data – aerial surveys

In addition to the network of continuously recording temperature dataloggers, a helicopter-mounted thermal infrared radiation (TIR) sensor and color video camera was used to take TIR and visible color images of selected segments of the streams and rivers in the watershed to provide a spatially continuous image of surface temperature. Surveys of the selected segments were conducted during August of 2001, 2002, and 2003 as follows:

- Aerial Surveys on August 12-14, 2001:
  - Chiwawa River 12-Aug-01
  - Wenatchee River 13-Aug-01
  - Little Wenatchee River 13-Aug-01
  - Nason Creek 14-Aug-01
- Aerial Surveys on August 16, 2002:
  - Wenatchee River 16-Aug-02
  - Icicle Creek 16-Aug-02
- Aerial Surveys on August 11-12, 2003:
  - Mission Creek 11-Aug-03
  - Brender Creek 11-Aug-03
  - Peshastin Creek 11-Aug-03
  - Chumstick Creek 11-Aug-03
  - Nason Creek 12-Aug-03

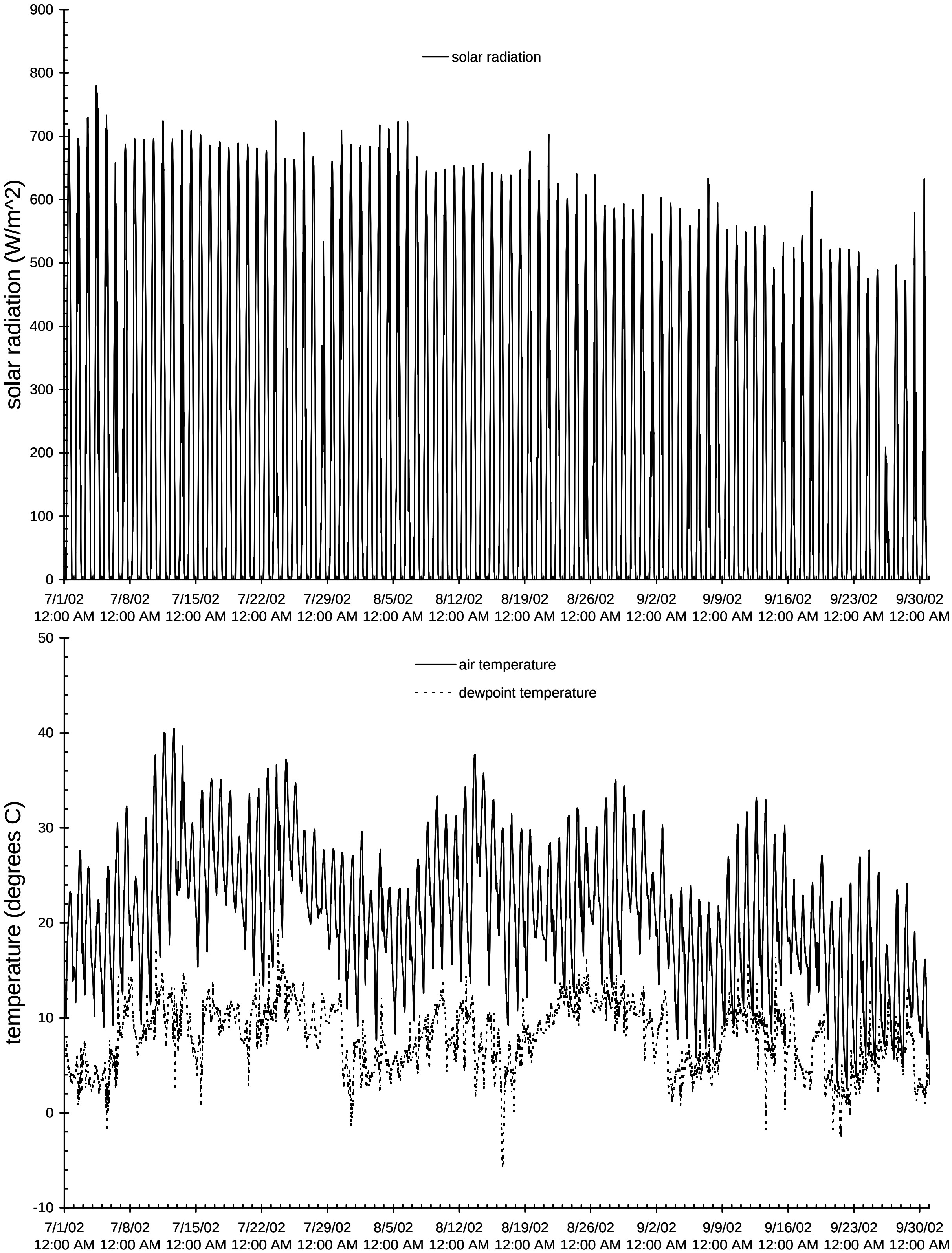
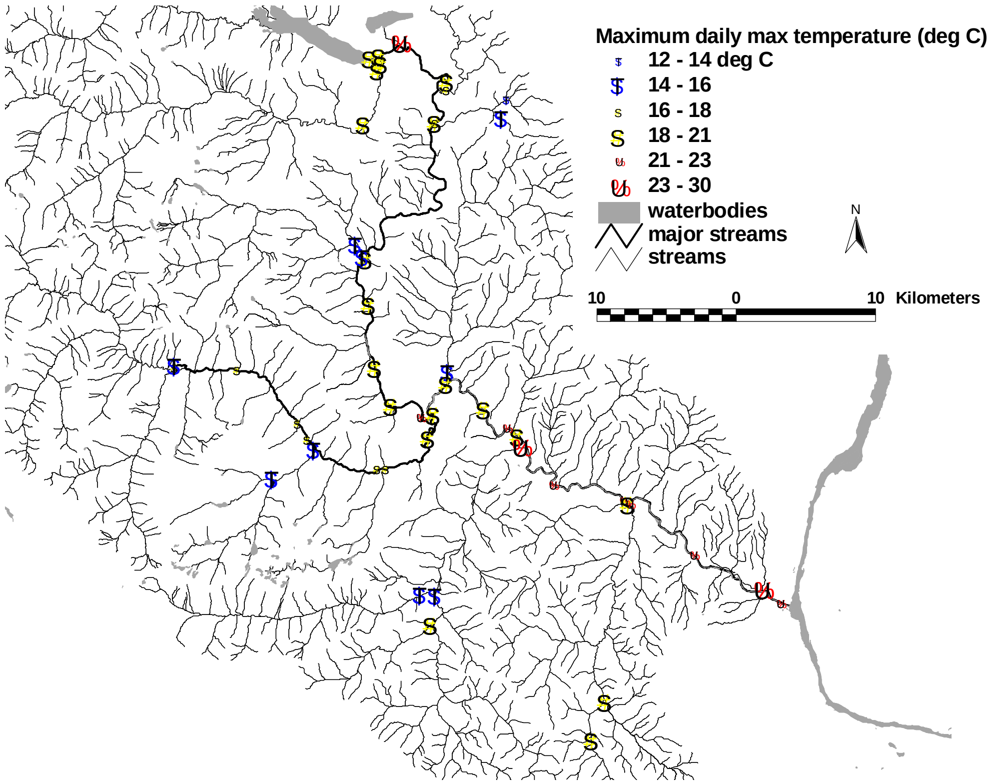



Figure 3. Regional solar radiation, air temperatures, and dewpoint temperatures (at the Wenatchee WSU TFREC station) during July-September 2002.

Table 4. Summary of maximum water temperatures in the Wenatchee basin during 2002.

| Agency (1) | Station | Longitude (decimal degrees) | Latitude (decimal degrees) | Description | Water Quality Class | Maximum 7-day-average daily maximum water temp-erature during 2002 (deg C) | | Maximum daily maximum water temp-erature during 2002 (deg C) | |
|---|---|---|---|---|---|---|---|---|---|
| Ecy WSU | 45FL00.3 | -120.6947 | 47.8181 | Fish Lake outlet | AA | 23.1 | | 23.7 | |
| Ecy WSU | 45PC00.3 | -120.5789 | 47.5578 | Peshastin RM0.3 | A | 22.1 | | 23.4 | |
| Ecy WSU | 45HR00.1 | -120.3492 | 47.4658 | Highline ditch return | A | 21.9 | | 25.5 | |
| Ecy WSU | 45WR05.3 | -120.4142 | 47.4883 | Wenatchee RM05.3 | A | 21.6 | | 22.2 | |
| Ecy WSU | 45WR00.5 | -120.3313 | 47.4572 | Wenatchee RM00.5 | A | 21.4 | | 22.1 | |
| Ecy WSU | 45WR10.2 | -120.4808 | 47.5231 | Wenatchee RM10.2 | A | 21.3 | | 21.8 | |
| Ecy WSU | 45WR18.7 | -120.5920 | 47.5701 | Wenatchee RM18.7 | A | 21.1 | | 21.8 | |
| Ecy WSU | 45MC00.1 | -120.4749 | 47.5213 | Mission RM0.1 | A | 21.0 | | 22.2 | |
| Ecy WSU | 45WR14.1 | -120.5478 | 47.5333 | Wenatchee RM14.1 | A | 20.9 | | 21.4 | |
| Ecy WSU | 45WR18.1 | -120.5809 | 47.5650 | Wenatchee RM18.1 | A | 20.4 | | 20.8 | |
| Ecy WSU | 45WR20.9 | -120.6135 | 47.5823 | Wenatchee RM20.9 | A | 19.9 | | 20.3 | |
| Ecy WSU | 45WR49.1 | -120.6491 | 47.7937 | Wenatchee RM49.1 | AA | 19.9 | | 20.6 | |
| Ecy WSU | 45WR35.9 | -120.7267 | 47.6791 | Wenatchee RM35.9 | AA | 19.7 | | 20.2 | |
| USFS | 45NC00.4 | -120.7124 | 47.8053 | Nason RM0.4 | AA | 19.4 | | 20.0 | |
| Ecy WSU | 45WR23.6 | -120.6492 | 47.5988 | Wenatchee RM 23.6 | A | 19.3 | | 19.8 | |
| Ecy WSU | 45WR33.0 | -120.7231 | 47.6493 | Wenatchee RM33.0 | AA | 19.3 | above non-core | 19.9 | above class A |
| USFS | 45PC10.9 | -120.6636 | 47.4430 | Peshastin RM10.9 | A | 19.1 | | 20.0 | |
| Ecy SHU | 45B050 | -120.6613 | 47.5791 | Icicle RM0.2 | A | 19.1 | | 20.0 | |
| Ecy WSU | 45WR46.4 | -120.6609 | 47.7672 | Wenatchee RM46.4 | AA | 19.0 | | 19.4 | |
| Ecy SHU | 45J070 | -120.7155 | 47.8008 | Nason RM0.8 | AA | 18.9 | | 19.7 | |
| Ecy WSU | 45WR30.3 | -120.7171 | 47.6090 | Wenatchee RM30.3 | AA | 18.9 | | 19.4 | |
| Ecy WSU | 45WR53.9 | -120.7230 | 47.8086 | Wenatchee RM53.9 | AA | 18.9 | | 20.4 | |
| USFS | 45NC03.8 | -120.7291 | 47.7660 | Nason RM3.8 | AA | 18.9 | | 19.6 | |
| USFS | 45WR28.1 | -120.7018 | 47.5843 | Wenatchee RM28.1 | AA | 18.6 | | 19.1 | |
| Ecy WSU | 45BR00.1 | -120.4759 | 47.5214 | Brender RM0.1 | A | 18.5 | | 19.0 | |
| Ecy SHU | 45A240 | -120.7141 | 47.8099 | Wenatchee RM53.5 | AA | 18.0 | | 18.9 | |
| Ecy WSU | 45CD00.1 | -120.6744 | 47.5768 | Cascade Orchard ditch | A | 17.8 | | 21.3 | |
| USFS | 45MCEF | -120.4979 | 47.3938 | Mission (East Fork) | A | 17.6 | | 18.6 | |
| USFS | 45MC12.7 | -120.5108 | 47.3687 | Devils Gulch | A | 17.4 | | 18.1 | |
| Ecy WSU | 45IC02.3 | -120.6667 | 47.5636 | Icicle RM02.3 | A | 17.4 | | 18.4 | |
| Ecy WSU | 45IC05.9 | -120.7147 | 47.5435 | Icicle RM05.9 | AA | 17.1 | | 17.9 | |
| USFS | 45IC05.6 | -120.7069 | 47.5439 | Icicle RM05.6 | AA | 16.9 | | 17.6 | |
| Ecy WSU | 45CW00.5 | -120.6495 | 47.7884 | Chiwawa RM0.5 | AA | 16.6 | above core | 17.3 | |
| Ecy WSU | 45IC11.4 | -120.7908 | 47.5732 | Icicle RM11.4 | AA | 16.4 | | 17.3 | abv class AA |
| Ecy WSU | 45IC09.9 | -120.7819 | 47.5628 | Icicle RM09.9 | AA | 16.3 | | 16.8 | |
| Ecy WSU | 45BC00.1 | -120.6608 | 47.7670 | Beaver RM0.1 | AA | 15.8 | | 16.8 | |
| Ecy WSU | 45CS00.3 | -120.6476 | 47.6053 | Chumstick RM0.3 | A | 15.4 | | 15.9 | |
| Ecy WSU | 45IC23.4 | -120.9081 | 47.6086 | Icicle RM23.4 | AA | 15.4 | | 16.1 | |
| Ecy WSU | 45IC15.0 | -120.8485 | 47.6072 | Icicle RM15.0 | AA | 15.4 | | 16.1 | |
| USFS | 45PC09.3 | -120.6593 | 47.4608 | Peshastin RM9.3 | AA | 14.8 | | 15.3 | |
| USFS | 45IN00.7 | -120.6733 | 47.4619 | Ingalls RM0.7 | AA | 14.6 | | 15.2 | |
| Ecy WSU | 45EC00.1 | -120.7747 | 47.5547 | Eightmile RM0.1 | AA | 14.4 | | 15.1 | |
| Ecy WSU | 45JC00.1 | -120.9074 | 47.6085 | Jack RM0.1 | AA | 14.2 | | 14.9 | |
| USFS | 45BCSF | -120.5960 | 47.7692 | Beaver (South Fork) | AA | 14.2 | | 14.9 | |
| Ecy SHU | 45G060 | -120.7288 | 47.6796 | Chiwaukum RM0.2 | AA | 13.8 | | 14.6 | |
| Ecy WSU | 45EC02.7 | -120.8139 | 47.5360 | Eightmile RM2.7 | AA | 13.6 | | 15.9 | |
| USFS | 45CH00.8 | -120.7354 | 47.6873 | Chiwaukum RM0.8 | AA | 13.5 | | 14.3 | |
| Ecy WSU | 45MT00.1 | -120.8134 | 47.5342 | Mountaineer RM0.1 | AA | 12.8 | | 13.9 | |
| USFS | 45BCNF | -120.5927 | 47.7819 | Beaver (North Fork) | AA | 12.3 | | 12.9 | |

1) Agency abbreviations:
- Ecy WSU: Department of Ecology, Watershed Studies Unit
- Ecy SHU: Department of Ecology, Stream Hydrology Unit
- USFS: United States Forest Service



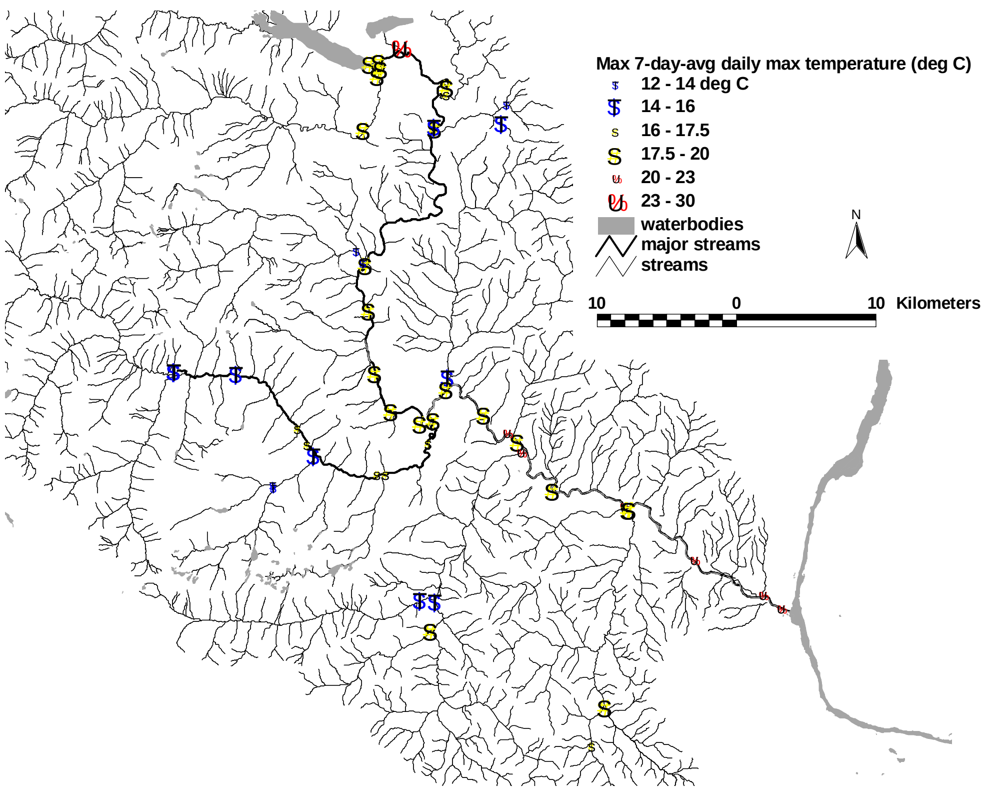
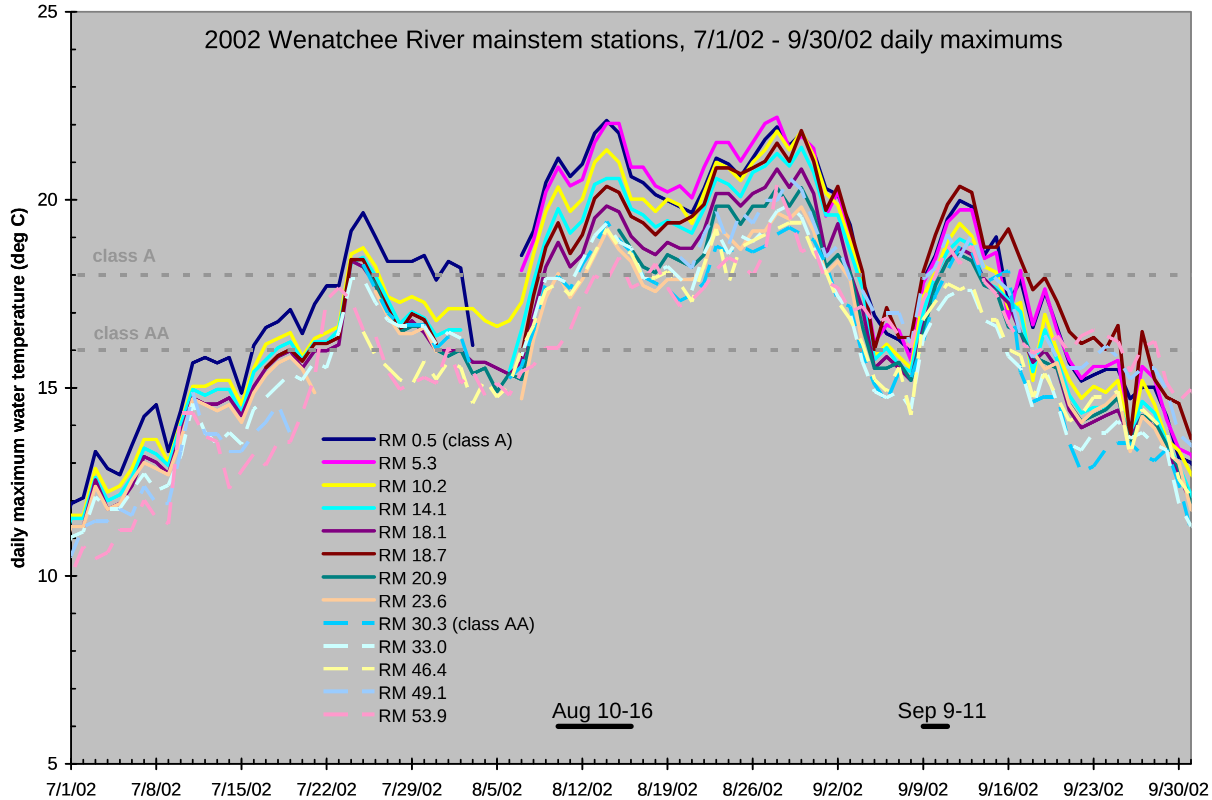




Figure 10. The highest daily maximum (upper map) and highest 7-day averages of daily maximum (lower map) water temperatures in the Wenatchee River and its tributaries during 2002.



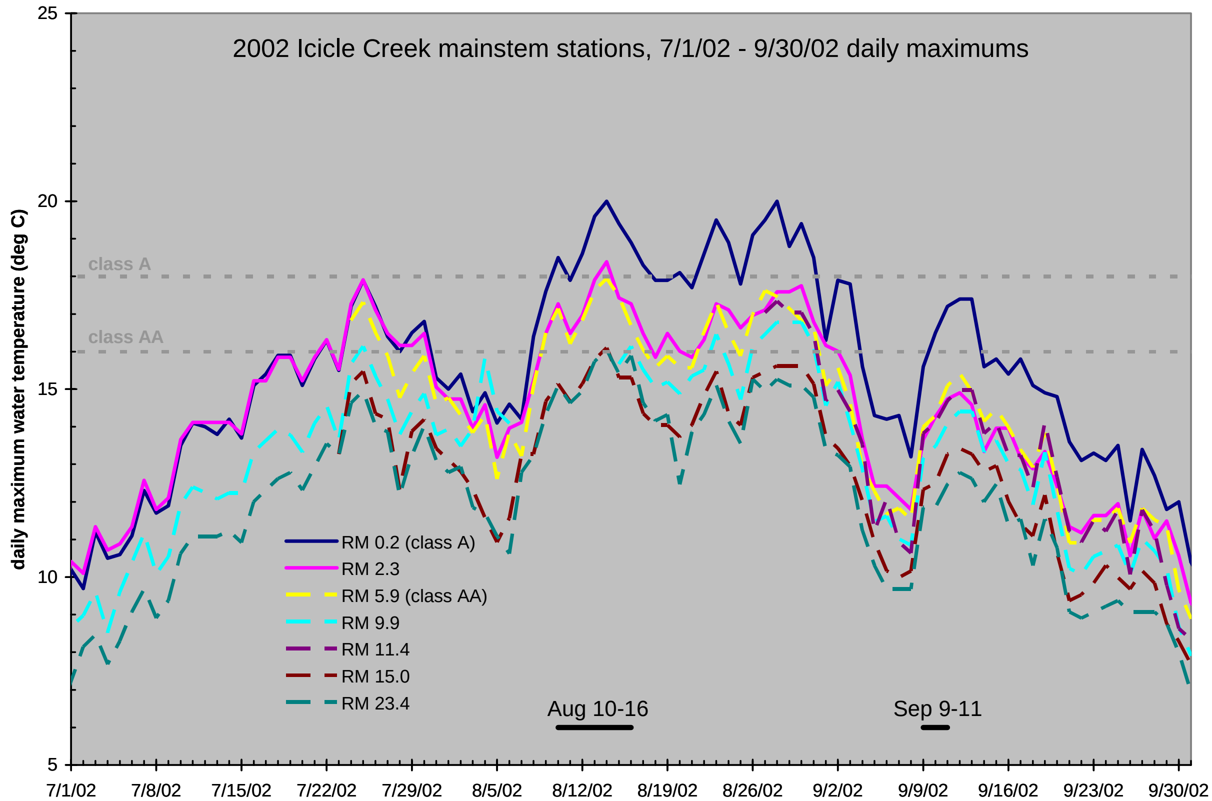




Figure 11. Daily maximum water temperatures in the Wenatchee River and Icicle Creek from July to September 2002.

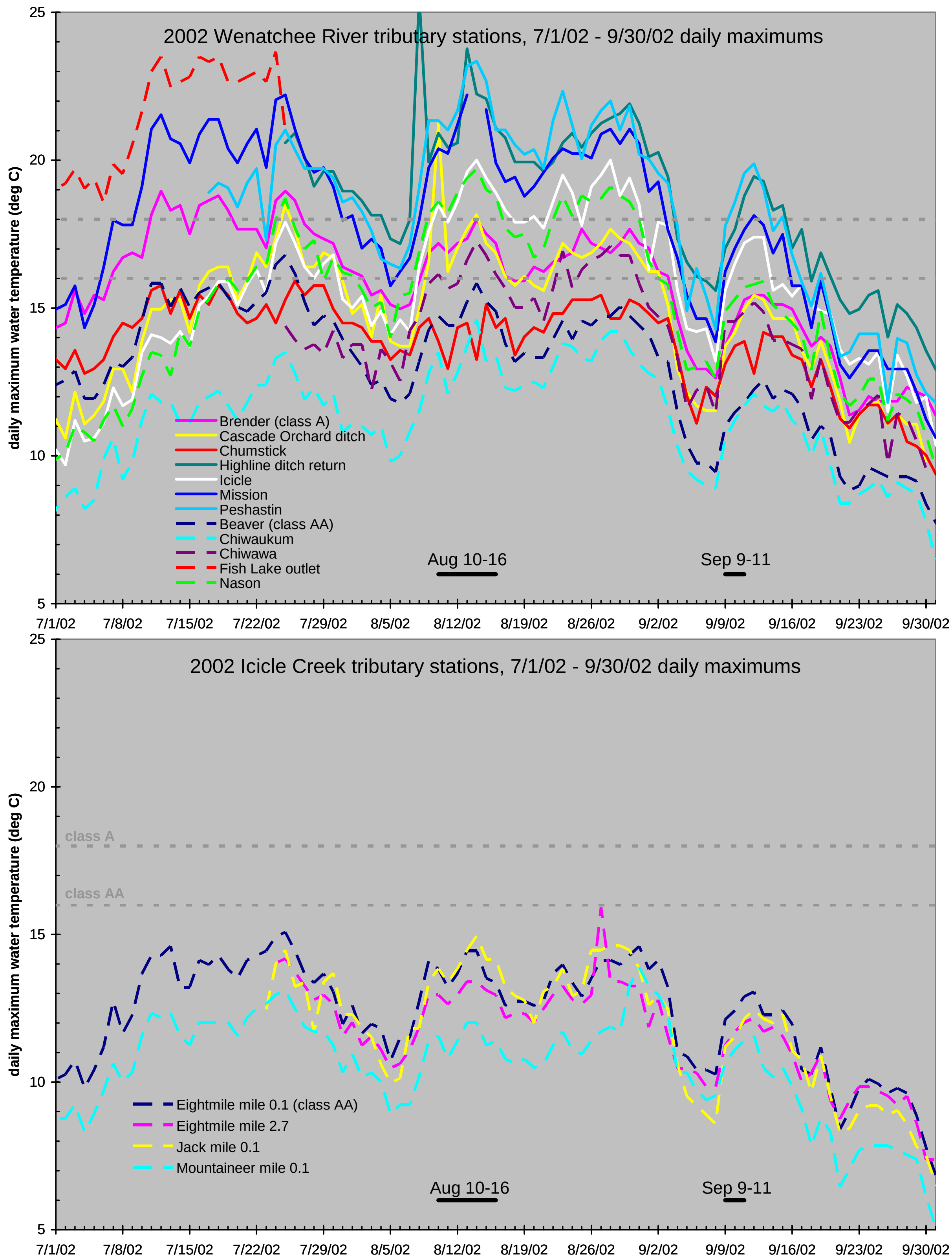



Figure 12. Daily maximum water temperatures in tributaries of the Wenatchee River and Icicle Creek from July to September 2002.

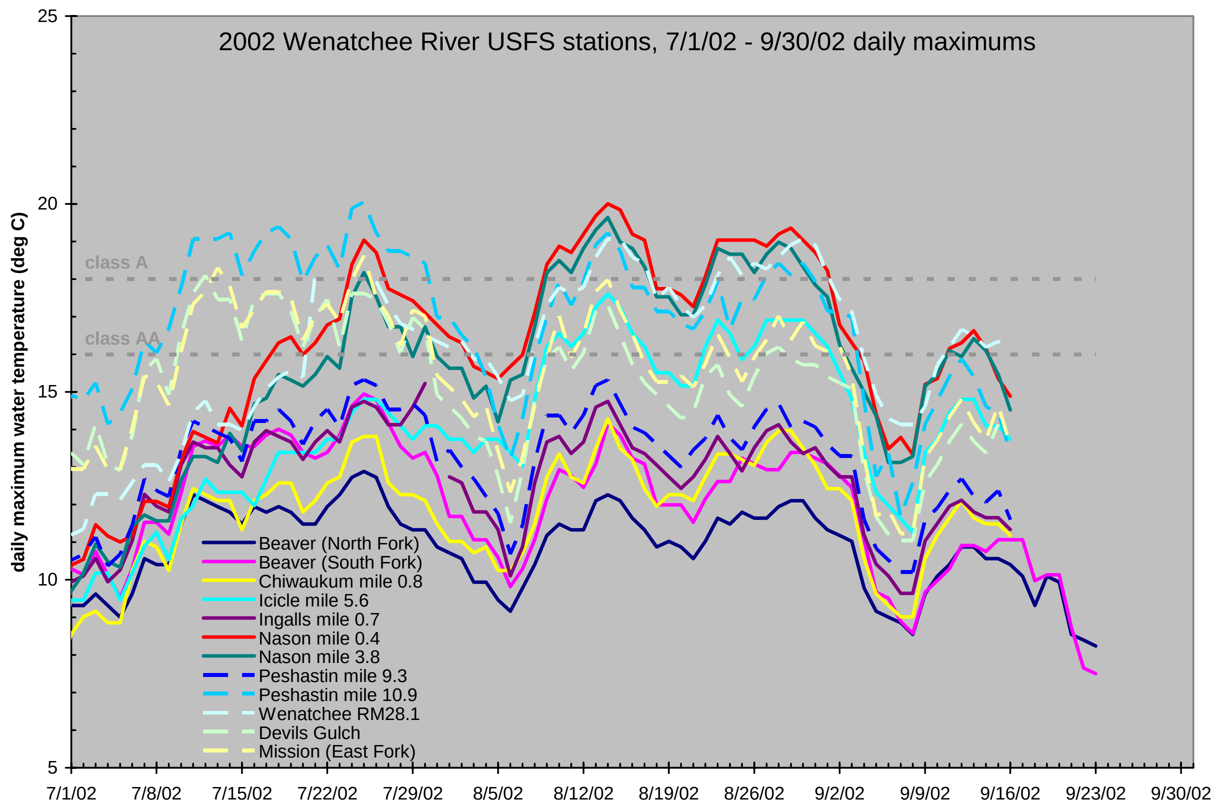



Figure 13. Daily maximum water temperatures at USFS stations in Wenatchee River watershed from July to September 2002.

An image browser was developed to view the TIR and color video images from 2001, 2002, and 2003. Copies of the browser software and TIR and color imagery from the aerial surveys are available on the Web at the following location [note to reviewers: the TIR imagery is not on the Web yet but can be viewed over Ecology's Intranet by entering the following address in your Web browser. If you want to review the TIR imagery but don't have access to Ecology's Intranet, you can request a copy on CD from Greg Pelletier or Dave Schneider]: http://aww.ecydev/apps/watersheds/temperature/tir/wenatchee/

The TIR files on the Web also include Excel spreadsheets of longitudinal profiles of stream temperatures that were recorded during the TIR surveys and Arcview shapefiles of the water temperatures that were estimated from the TIR images. This imagery and data will be used by the Department of Ecology in preparation of the future draft and final technical study reports for the temperature TMDL project.

## Stream flow data

Continuous stream flows were recorded at locations in the Wenatchee River watershed as described by Bilhimer et al, 2002. The continuous flow measurements can be browsed or downloaded from the Web at the following location: http://www.ecy.wa.gov/apps/watersheds/flows/station.asp?sta=45A100

## Hydraulic geometry

The channel width, depth, and velocity have an important influence on the sensitivity of water temperature to the flux of heat. The general relationships between wetted width, depth, velocity, and flow at USGS gaging stations in the watershed were evaluated by Tom Robison (personal communication, 2003) and are shown in Table 5. Average velocities of selected stream segments in the Wenatchee River were measured during September 9-11, 2002 using a dye tracer (Table 6).

Table 5. Hydraulic geometry coefficients for USGS gaging stations in the Wenatchee River basin (personal communication with Tom Robison, USFS).

| USGS station | Station Name | Drainage area (mi2) | *Channel geometry coefficients* Width a W=aQ^b (W in ft, Q in cfs) | b | Depth c D=cQ^f (D in ft, Q in cfs) | f | Velocity k V=kQ^m (V in fps, Q in cfs) | m |
|---|---|---|---|---|---|---|---|---|
| 12455000 | Wenatchee R below Lake Wen | 273 | 171.4194 | 0.049074 | 0.143704 | 0.451795 | 0.040645 | 0.498944 |
| 12456500 | Chiwawa R near Plain | 172 | 78.98489 | 0.055248 | 0.118069 | 0.439834 | 0.108395 | 0.502789 |
| 12457000 | Wenatchee R at Plain | 591 | 73.73556 | 0.115108 | 0.199669 | 0.38671 | 0.067978 | 0.498211 |
| 12458000 | Icicle Cr above Snow Cr near Lea | 193 | 53.7032 | 0.0796 | 0.5623 | 0.2515 | 0.0331 | 0.6691 |
| 12459000 | Wenatchee R at Peshastin | 1000 | 175.8053 | 0.03242 | 0.37248 | 0.341674 | 0.015273 | 0.625946 |
| 12461000 | Wenatchee R at Dryden | 1155 | 114.0807 | 0.082213 | 0.15021 | 0.398723 | 0.058778 | 0.518353 |
| 12462500 | Wenatchee R at Monitor | 1301 | 115.376 | 0.07 | 0.1808 | 0.3908 | 0.0479 | 0.5394 |
| *Average of Wenatchee R stations:* | | | *130.0834* | *0.069763* | *0.209373* | *0.39394* | *0.046115* | *0.536171* |

Table 6. Stream segment velocities measured during a dye study during September 9-11, 2002.

| date | | segment upstream RM | segment downstream RM | segment upstream distance from headwater (Km) | segment downstream distance from headwater (Km) | segment velocity (m/s) | Flow during dye study at Monitor (USGS 12462500) (cfs) | Estimated velocity (m/s) for September 9-11, 2002 average flow (cfs) at USGS 12462500 = 824.67 | Estimated velocity (m/s) for August 10-16, 2002, flow (cfs) at USGS 12462500 = 1587.14 |
|---|---|---|---|---|---|---|---|---|---|
| 9/12/02 | 8:20 PM | | 53.6 | | 0 | | | | |
| 9/12/02 | 1:15 AM | 53.6 | 50.4 | 0.0 | 5.1 | 0.291 | 760 | 0.304 | 0.432 |
| 9/12/02 | 7:00 AM | 50.4 | 46.5 | 5.1 | 11.4 | 0.303 | 760 | 0.317 | 0.450 |
| | | | 46.2 | | | | | | |
| 9/11/02 | 9:00 AM | 46.2 | 41.8 | 11.9 | 19.0 | 0.536 | 785 | 0.551 | 0.782 |
| 9/11/02 | 3:00 PM | 41.8 | 35.6 | 19.0 | 29.0 | 0.462 | 785 | 0.474 | 0.674 |
| 9/10/02 | 11:45 PM | 35.6 | 32.0 | 29.0 | 34.8 | 0.411 | 831 | 0.409 | 0.581 |
| 9/11/02 | 3:00 AM | 32.0 | 30.9 | 34.8 | 36.5 | 0.151 | 785 | 0.155 | 0.221 |
| 9/11/02 | 8:00 AM | 30.9 | 26.4 | 36.5 | 43.8 | 0.402 | 785 | 0.413 | 0.587 |
| 9/10/02 | 8:00 AM | 26.4 | 23.8 | 43.8 | 48.0 | 0.399 | 831 | 0.397 | 0.564 |
| 9/10/02 | 11:00 AM | 23.8 | 21.5 | 48.0 | 51.7 | 0.343 | 831 | 0.341 | 0.485 |
| | | | 16.2 | | | | | | |
| 9/9/02 | 8:30 AM | 16.2 | 11.3 | 60.2 | 68.1 | 0.584 | 858 | 0.572 | 0.812 |
| 9/9/02 | 12:30 PM | 11.3 | 7.1 | 68.1 | 74.8 | 0.469 | 858 | 0.460 | 0.653 |
| 9/9/02 | 3:30 PM | 7.1 | 3.2 | 74.8 | 81.1 | 0.581 | 858 | 0.569 | 0.808 |

## Analytical framework

Data collected during this TMDL study allows the development of a temperature simulation model that is both spatially continuous and which spans full-day lengths (quasi-dynamic steady-state diel simulations). The GIS and modeling analyses use three specialized software tools:

- ODEQ's Ttools extension for Arcview (ODEQ, 2001) was used to sample and process GIS data for input to the Shade and QUAL2K models.
- Ecology's Shade model (Ecology, 2003a) was used to estimate effective shade along the mainstems of the major tributaries in the Wenatchee River basin. Shade calculations that have been completed to date only include the effect of topography. Future analyses will also include the effect of riparian vegetation on shade. Effective shade was calculated at 100-meter intervals along the streams and then averaged over 500-meter intervals for input to the QUAL2K model.
- The QUAL2Kw model (Pelletier and Chapra, 2004; Chapra and Pelletier, 2003) was used to calculate the components of the heat budget and to simulate water temperatures. QUAL2Kw simulates diurnal variations in stream temperature for a steady flow condition. QUAL2Kw was applied by assuming that flow remains constant for a given condition such as a 7-day or 1-day period, but key variables are allowed to vary with time over the course of a day. For temperature simulation, the solar radiation, air temperature, relative humidity, headwater temperature, and tributary water temperatures were specified or simulated as diurnally varying functions. QUAL2Kw uses the kinetic formulations for the components of the surface water heat budget that are shown in Figure 4 and described in Chapra (1997). Diurnally varying water temperatures at 500-meter intervals along the streams in the Wenatchee River basin were simulated using a finite difference numerical method. Calibration of the model to in-stream data along the mainstems of the streams and rivers will be presented in more detail in the final TMDL report.

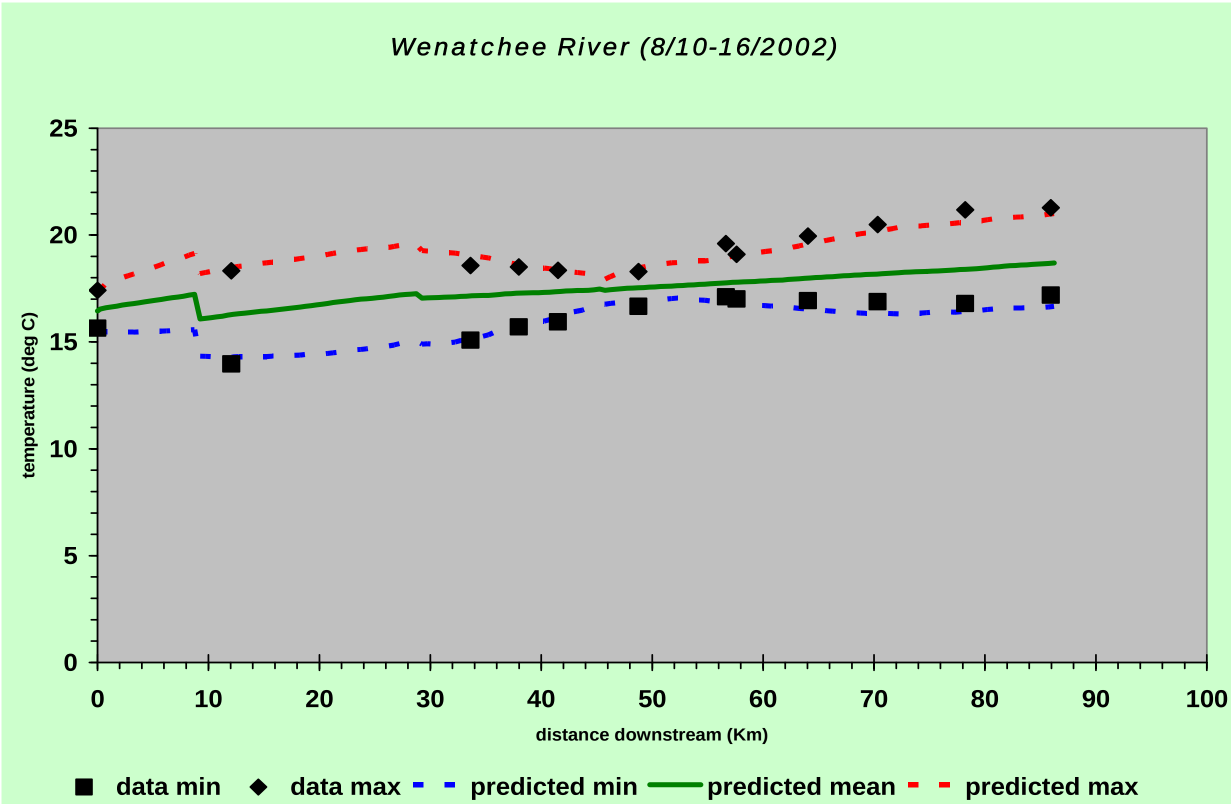
All input data for the Shade and QUAL2Kw models are longitudinally referenced, allowing spatial and/or continuous inputs to apply to certain zones or specific river segments. Model input data were determined from available GIS coverages using the Ttools extension for Arcview, or from data collected by Ecology or other data sources. Detailed spatial data sets were developed for the following parameters for model calibration and verification (the analyses to date are preliminary and partially completed and will be refined and completed for the future technical study report):

- The Wenatchee River and Icicle Creek were mapped at 1:3,000 scale from 1-meter-resolution Digital Orthophoto Quads (DOQ).
- Riparian vegetation has not yet been evaluated but will be analyzed and presented in a future report.
- Near-stream disturbance zone (NSDZ) widths were digitized at 1:3000 scale.
- West, east, and south topographic shade angle calculations were made from the 10-meter DEM grid using ODEQ's Ttools extension for Arcview.

- Stream elevation and gradient were sampled from the 10-meter DEM grid with the Arcview Ttools extension. Gradient was calculated from the longitudinal profiles of elevation from the 10-meter DEM.
- Aspect (stream flow direction in decimal degrees from north) was calculated by the Ttools extension for Arcview.
- The daily minimum and maximum observed temperatures for the boundary conditions at the headwaters and tributaries were used as input to the QUAL2Kw model for the calibration and verification periods. The QUAL2Kw model was tested in a preliminary fashion using data collected during August 10-16, 2001 and September 9-11, 2002 respectively.
- Flow balances for the preliminary calibration and verification periods were estimated from field measurements and gage data of flows made by Ecology and the USGS. A flow balance spreadsheet of the stream networks for the Wenatchee River and Icicle Creek was constructed to estimate surface water and groundwater inflows by interpolating between the gaging stations.
- Hydraulic geometry (wetted width, depth, and velocity as a function of flow) was estimated using wetted widths that were digitized from DOQs and scaled to different river flows using the average power functions from the USGS gaging stations. Velocities were estimated from dye study data and scaled to different river flows using the average power functions from the USGS gaging stations.
- The temperature of groundwater is often assumed to be similar to the mean annual air temperature (Theurer et al, 1984). Calibration of the QUAL2Kw model involved selection of the temperature of diffuse inflows ranging from the estimated temperature of ground water temperature to observed temperatures of surface water tributaries.
- Air temperature, relative humidity, and cloud cover were estimated from meteorological data recorded in Wenatchee. Future refinement of the meteorological inputs for the QUAL2Kw model will include the observed meteorology at the stations throughout the watershed occupied by Ecology and other agency stations during the study year to represent the conditions for the calibration and verification periods.

## Preliminary calibration results of the QUAL2Kw model

A preliminary calibration of the QUAL2Kw model has been set up for the period of August 10-16, 2002 and September 9-11, 2002 (Figure 14). The model results compare reasonably well to the observed water temperatures during these periods. The model reproduces the observed spatial pattern of temperatures. Model calibration will be refined and the input data and output results for various scenarios will be explained in more detail in a future technical report.



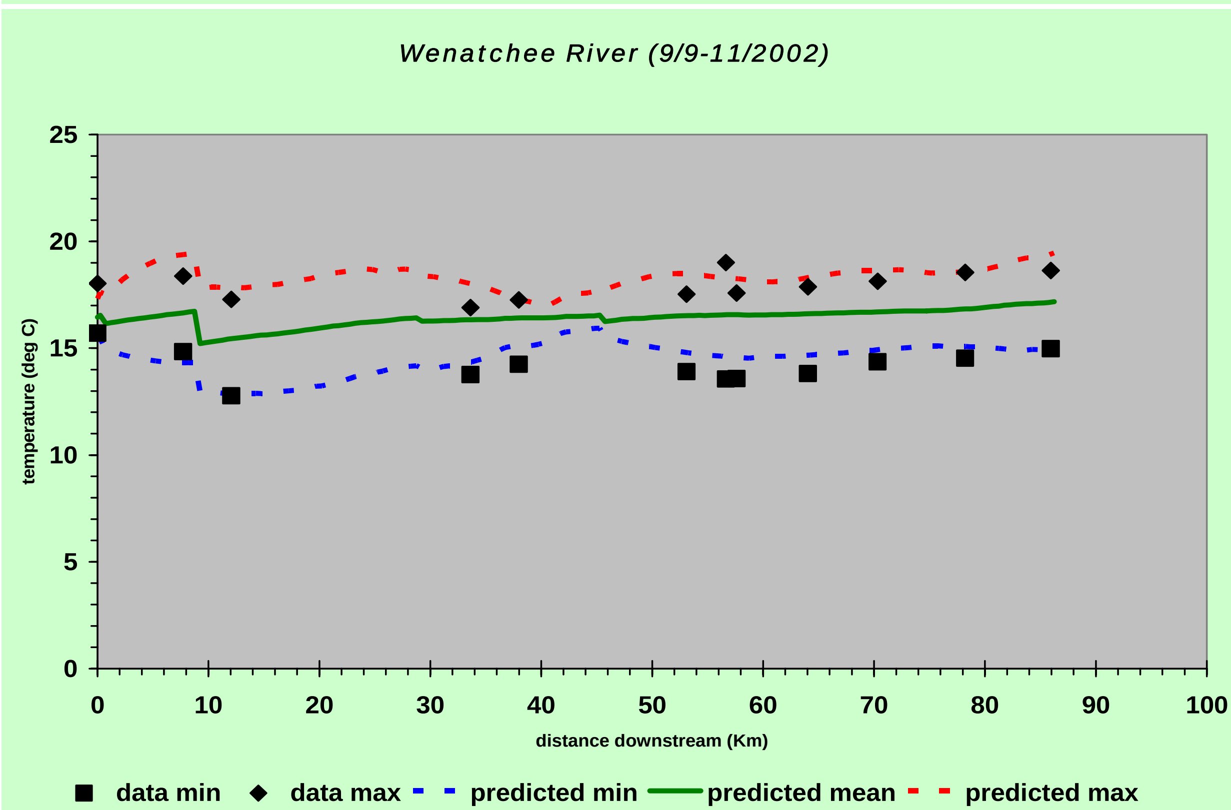




Figure 14. Predicted and observed water temperatures in the Wenatchee River for August 10-16, 2002 and September 9-11, 2002.

# Conclusions and recommendations

The observed stream temperatures in the Wenatchee River watershed during 2002 showed that current conditions at many locations are warmer than the current and proposed revised water quality criteria. In addition, many locations were found to be cooler than the temperature criteria. In general, warmer temperatures were found at downstream locations in the Wenatchee River and Icicle Creek and cooler temperatures were found in relatively small tributaries or headwater locations.

The preliminary model calibration showed that temperatures in the Wenatchee basin can be accurately estimated using a numerical model. The preliminary model does a good job of reproducing the spatial patterns of water temperature in the Wenatchee River. Ecology will refine the calibration of the model and use it to evaluate various scenarios and recommend load allocations in consideration of the water quality criteria. Ecology expects that the model accuracy will be improved with improved inputs for key variables such as meteorology, effective shade, and hydraulic geometry.

Ecology will continue to process the available data from the field work in 2002 and 2003 to develop the technical study report for the temperature TMDL. In addition, the QUAL2Kw model will be calibrated and confirmed to address 303(d) listings for temperature throughout the basin and propose load allocations for non-point sources and wasteload allocations for point sources to protect the water quality standards for temperature.

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# Appendix A. Use designations of the revised WAC 173-201a for WRIA 45 (Wenatchee)

| 2003 Revised WAC 173-201a, Table 602, WRIA 45 (Wenatchee) | Aquatic Life Uses | | | | | | Recreational Uses | | | Water Supply Uses | | | | Misc. Uses | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Use Designations for Fresh Waters by Water Resource Inventory Area (WRIA) | Char | Core Salmon/Trout | Non-Core Salmon/Trout | Salmon/Trout Rearing | Redband Trout | Warm Water Species | Ex Primary Cont | Primary Cont | Secondary Cont | Domestic Water | Industrial Water | Agricultural Water | Stock Water | Wildlife Habitat | Harvesting | Commerce/Navigation | Boating | Aesthetics |
| Chikamin Creek and all tributaries. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Chiwaukum Creek and South Fork Chiwaukum Creek: All waters (including tributaries) above the junction. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Chiwawa River from mouth to unnamed creek at longitude -120.8409 and latitude 48.0595 (near Phelps Creek). | | ✓ | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Chiwawa River and all tributaries above unnamed creek at longitude -120.8409 and latitude 48.0595 (near Phelps Creek). | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Dry Creek and Chumstick Creek: All waters (including tributaries) above the junction, except those waters in or above the Wenatchee National Forest. | ✓ | | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Dry Creek and Chumstick Creek: All waters (including tributaries) above the junction that are in or above the Wenatchee National Forest. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Eagle Creek and the unnamed tributary at longitude -120.5165 and latitude 47.6544: All waters (including tributaries) above the junction, except those waters in or above the Wenatchee National Forest. | ✓ | | | | | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Eagle Creek and the unnamed tributary at longitude -120.5165 and latitude 47.6544: All waters (including tributaries) above the junction that are in or above the Wenatchee National Forest. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Icicle Creek and all tributaries above unnamed creek at longitude -120.9547 and latitude 47.6206 (near French Creek). | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Little Giant Creek and all tributaries. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Rock Creek and all tributaries. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Second Creek and the unnamed tributary at longitude -120.5935 and latitude 47.7384: All waters (including tributaries) above the junction. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Van Creek and the unnamed tributary at longitude -120.5373 and latitude 47.6722: All waters (including tributaries) above the junction. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wenatchee River from Wenatchee National Forest boundary (river mile 27.1) to Chiwawa River. | | ✓ | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wenatchee River and all tributaries upstream of Chiwawa River. | ✓ | | | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

# Appendix B. Instream water temperature station disposition report for the 2002 data collected in the Wenatchee River watershed

Wenatchee River at outlet of Lake Wenatchee

This station was located on the left bank of the Wenatchee above the mouth of Nason Creek. The site was accessed through the maintenance road at North Lake campground campsite #187. The relative humidity sensor was attached to a snag and the water tidbit was on a concrete block approximately 30 feet away from the left bank. No problems were encountered with the water tidbit, but the air temperature and relative humidity sensor was having problems launching correctly from the laptop. A tidbit was placed in the solar radiation shield on 8/28 to replace the RH sensor. The air temperature data was lost from 7/18 till 8/28, and relative humidity was lost from 7/18 till the end of the study period.

Wenatchee River above Chiwawa Creek

This station was located next to the west side of the metal bulkhead at Chiwawa community water station. The water tidbit was attached to a concrete block and was pulled out several times during the summer by unknown vandals. This tidbit began logging on June 29, 2002. It was found out of water on 7/25 and the data was clipped for the dry period from 7/19 at 10:00am to the last data point on 7/25. The same tidbit was then redeployed. It was checked again on 8/16, it was pulled out of the water again but was not downloading correctly, the field tech did not replace the logger at this time. The tidbit was checked again on 8/20 when it was found to have a crack in the sensor casing. The sensor was replaced with a new tidbit on 8/20 and this one worked fine and was not vandalized again. The tidbit was removed on 10/16 at 4:00pm.

Fish Lake Creek

This station was located above the culvert at the Sno-Park parking lot on Chiwawa Loop Rd. The stream went dry sometime between 7/25 and 8/5 but it is difficult to determine the exact time when the air and the water tidbits are compared. The tidbit was still dry when the station was removed on 10/16. Therefore all water temperature data from 7/25 11:00am till the end of the study period has been removed from the final dataset.

Chiwawa Creek near mouth

This station was located at the Chiwawa Creek Fish Hatchery near the raft pull-out above the fish screens. It was first installed on 4/25 but the water tidbit was lost during the high June flows, and it was replaced on 7/25. There are no other qualifications to the data.

Wenatchee River above Beaver Creek

This station was located at the raft pull-out next to SR209 approximately 50 feet above the confluence with Beaver Creek. The air temperature station was shared with the Beaver Creek water tidbit station. The original water tidbit was lost during the June flows and was replaced on

7/25.  When retrieved on 10/16 the water tidbit was out of the water by 0.1feet.  A comparison with the air temperature showed that the water tidbit was exposed during the early morning on 10/16 so all water temperature data for this day was cut.

Beaver Cr near mouth

This station was located on Beaver Creek approximately 30 feet upstream from its confluence with the Wenatchee River.  The air temperature tidbit was shared with the Wenatchee R. above Beaver Creek station.  When the water tidbit was checked on 7/25 it was found covered by sand and debris.  It was cleaned off and did not encounter that problem again for the rest of the study period.

Wenatchee River above Chiwaukum Cr.

This station was located on the right bank of the Wenatchee River approximately 20 feet upstream of the confluence with Chiwaukum Creek.  The air temperature and relative humidity sensor encountered problems with the field laptop when downloading the data.  Apparently the power conservation feature of the laptop turned off communication to the COM port and didn't allow the datalogger to launch properly and it did not collect any data after the download on 7/25.  There is only air temperature and RH data for the period from 4/27 to 7/25.  The first water tidbit deployed on 4/27 was lost during the June high flows, and a replacement was installed on 7/25.  The water tidbit was also vandalized and left on the stream bank sometime between 14:30 and 15:00 hours on 8/10.  During a field check on 8/16 a replacement TI was installed and the original tidbit wasn't discovered until 8/21 during the stream channel survey.  There is a dry period 8/10 15:00 through 8/16 14:30 that was removed and one temperature data points were removed due to the tidbit being affected by the air temperatures on 8/21 18:30.  The time period after 10/26 was adjusted for Pacific Standard Time.

Wenatchee River at River Mile 33.0 (45WR33.0)

This station was located along Hwy 2 in Tumwater Canyon at the scenic pullout with the Adopt-A-Highway sign for the Sleeping Lady Resort.  This was one of the few stations that was not lost in the June flows.  Upon comparison with the air tidbit a dry period was determined from 8/2 – 8/6, and all data from 8/2 00:00 to 8/7 00:00 was removed from the final data set.

Wenatchee River abv Lake Jolanda (45WR32.3)

This station was located on the Wenatchee in Tumwater Canyon at the second pullout (heading north on Highway 2) past the candy and gift shop upstream from the Tumwater dam.  The water tidbit was determined to have gone dry and data for the following time periods were cut from the final data set. 7/4 16:30 – 7/8 06:30,   8/4 06:52 – 8/5 22:52, and 8/8 07:52.  The water tidbit was vandalized and not recovered after the last field check on 8/13.

Wenatchee River below Tumwater Dam

This station was located on the Wenatchee River approximately 0.63 miles downstream of the Tumwater Dam, and was accessed through a car pullout off Highway 2.

## Icicle Creek and tributaries

Icicle Creek above Jack Cr.

This station was located at the end of Forest Service Rd 615 approximately 160 feet above the mouth of the main channel of Jack Creek on the right bank of Icicle. There were no problems encountered at this station and the water tidbit stayed wet all summer long. No data needs qualifying.

Jack Cr. Near mouth

This station was located at the end of Forest Service Rd 615 on the channel that flows under the bridge at the end of this road. USGS maps and other existing coverages show the main channel of flow moving east from a point several hundred feet above this bridge, however I investigated this and found the stream channel has changed dramatically from when it was mapped (or was mapped incorrectly). The channel flowing under the bridge is the main channel and the incorrectly mapped segment is a high flow channel only that may only receive water during the high flow period in June. From mid-July to the end of the study period all of the water in the system was flowing through the channel with the tidbit. It is unclear (due to the lack of a specific observation during July) exactly when in July waters receded below the bank flowing into the high flow channel.
The first water tidbit installed in May was lost during the high June flows, and a replacement was installed on 7/23. The water station was located in the thalweg about 30 feet downstream from the bridge; the air station was attached to the underside of the bridge. No other problems were encountered with this station during the study period.

Icicle Creek at Ida Creek Campground

This station was located on Icicle Creek the Ida Creek campground. It was approximately in the thalweg of the channel just upstream of the braided segment of Icicle and downstream from the mouth of Ida Creek. The original water tidbit was lost during June high flows and a replacement was reinstalled on 7/23. No other problems were encountered with this station during the study period.

Icicle Creek below 4th of July Creek (formerly RM11.4)

This station was located near the left bank side of Icicle Creek at river mile 10.8, approximately 600 feet downstream of a partially blocking log jam. The main channel of flow is nearer the right bank, and this segment changed dramatically during the study period. During the installation and through most of July the stream flow was too high to be able to place the tidbit further into the middle of the stream, and the stream bottom characteristics were difficult to tell how the lower summer flows would change the site.

The tidbit download check on 7/23 discovered the tidbit had been lost during the high spring/early summer flows and a replacement water tidbit was installed. The field check on 8/16 found the instream tidbit out of water so it was reinstalled further out in towards the main channel of flow. This tidbit was checked again on 8/27 but was not downloading properly so another replacement was installed. No good data was retrieved from the first replacement tidbit, so the temperature dataset for this station only begins at 8/27 and lasts through 10/15.

It was past 8/16 that the water had dropped to a point where we could wade further into the stream for better tidbit placement at this station; thus the tidbit was kept where it was and reference temperature measurements were made in the main channel as well as in the side channel with the tidbit. After (some date) the tidbit was not representing the main channel water temperatures.

Icicle Creek at Bridge Creek Campground

This station was located near the right bank of Icicle Creek approximately 100 feet downstream of the bridge crossing the creek. It was moved twice during the study to keep it in the main area of streamflow. The instream tidbit was found dry on the 8/15 tidbit check and the total dry period determined from the air and water thermograph (8/7 00:00 - 8/15 08:50) was cut from the final dataset. No other data needs qualifying.

Mountaineer Creek near mouth

This station was located approximately 100 feet downstream of the FR 7601 road bridge crossing of Mountaineer Creek. The instream tidbit was in the thalweg and did not go dry at any point during the study period. No data needs qualifying.

Eightmile Creek above Mountaineer

This station was located approximately 10 feet upstream of the FR 7601 road bridge crossing Eightmile Creek. Due to high June streamflows and the 6 foot falls and cascades this station was not able to be installed until 7/24. There were no problems with the instream tidbit, however the air tidbit was “lost” for half a month in August and a replacement was installed. Fortunately the original sensor was still there and the replacement remained in the field for the rest of the study period.

Eightmile Creek near mouth

This station was located (with landowner permission) approximately 50 feet upstream of the house, near the right bank. The water was well mixed due to small waterfalls and cascades throughout the reach and the tidbit never went dry until near the beginning of October. It was removed on 10/16 and was found 0.1 feet above the water surface, but the temperature data from the tidbit was consistent with the thermometer reading of the water temperature at the same spot. The cutting point for the instream data was determined from a comparison of air and water temperature data that the likely time when the instream tidbit was exposed to the air was around 10/10 so data was cut off at the end of 10/9.

Icicle Creek at Icicle/Peshastin Irrigation District

This station was located on Icicle Creek adjacent to the diversion canal for the Icicle/Peshastin Irrigation District. The location was accessed by the vehicle pull-out on Icicle Rd near the information kiosks. The station was installed late (7/24) and was not originally planned in the QAPP, but was added to provide more temperature data in the stream reach influenced by the diversions. There were no problems with either air or water tidbits. The instream tidbit did not go dry during the study period, however the creek water level dropped dramatically from September until the station was removed in October at which point the instream tidbit was only 0.25 feet below the water surface. The drop in streamflow is attributed to no precipitation locally or in the headwaters, and continued water withdrawal by the irrigation district; my visual estimate of water withdrawal from Icicle Creek was more than 50 percent of total streamflow diverted into the canal.

<u>Snow Creek near mouth</u>

<u>Icicle Creek above old channel (continuous flow gage)</u>

<u>Icicle Creek at East Leavenworth Road bridge crossing</u>

This station was located on the right bank of Icicle Creek immediately downstream of the East Leavenworth Road bridge crossing. On this reach the Creek goes from wadeable depths approximately 300 feet upstream, to depths up to 10 feet at the tidbit, and then wadeable again approximately 200 feet downstream. The instream tidbit was anchored on the creek bottom with a concrete block in about 7-8 feet of water. Comparisons of instream tidbit data with reference thermometer readings from near the water surface are very similar suggesting that this small pool was well mixed.

<u>Cascade Orchard Irrigation ditch return</u>

This station was located approximately 15 feet from the screen at the irrigation ditch return on Icicle Road. There was a staff gage at this site and a discharge rating curve was developed. The ditch was closed and empty on 10/1. There were no problems with either the air or instream tidbits. There were some periodic temperature spikes in the instream thermograph that could not be explained with only a stage correlation at this site. The temperature spikes in question occurred on the following dates and times: 5/24 14:30 at 10.29degC, 6/14 10:30 at 14.65 degC, and 8/10 12:11 at 20.6 degC. There was another temperature spike on 8/12 from 12:00 – 18:30 hours, however this was due to a ditch cleaning and was noted in the stage log by the watermaster. It is possible that the volume of water in the ditch changes dramatically during each day and that exchange wasn't captured by daily stage readings but could be apparent in the thermograph as a temperature spike when the stage drops below the water tidbit. The temperature spikes have been left in the final dataset as water temperatures.

<u>Wenatchee River above Chumstick Creek</u>

This station was located approximately 200 feet downstream of the Highway 2 bridge entering Leavenworth. Access was gained through a trail down to the river behind the Alpine Inn. The river flows through a steep valley and is constrained by the bridge upstream to create a very deep channel. There is rip-rap armoring both riverbanks and the water tidbit was attached to a cement block and dropped among the rip-rap. The river dropped quite a bit over the course of the study period and both exposing the instream tidbit to air and vandals. During one site visit, the instream tidbit and the cement block were found pulled out of the water and sitting on the edge of the rip-rap and the solar radiation shield for the RH probe had been tampered with and had two of the bottom plates missing. The following time periods were removed from the final dataset because they represented times when the instream tidbit was dry: 7/21 08:00 thru 7/26 09:30, 8/1 00:00 thru 8/7 07:30, and 9/5 00:06 thru 9/18 04:36. Problems launching the RH probes with the field laptop resulted in air temperature and RH data from 6/29 00:00 thru 7/26 09:00.

Chumstick Creek at North Road culvert

This station was located approximately 7 feet upstream of the culvert on North Road just north of Leavenworth. The permanent flow gage on Chumstick Creek was upstream by more than 300 yards. The creek is at the bottom of a steep ravine, and there was an irrigation return 10 feet upstream of the instream tidbit so the water temperatures reflect the mix of the Chumstick and irrigation return. The mouth of Chumstick was another 600 yards downstream and there were no other surface water inputs downstream of the tidbit.

Wenatchee River below Chumstick Creek

This station was located on the Wenatchee River at a common pullout for rafters, unfortunately this was not identified until the instream tidbit was vandalized. After the vandalism was discovered the tidbit was moved downstream of the area in which rafters portaged their rafts out of the river. The stream channel appeared to have a fairly uniform bottom (observation made at low water) but was still not wadeable across a cross-section. The instream tidbit was found missing and replaced on 8/15 (the day before the FLIR flight). After the instream tidbit was moved no other problems were encountered with it.

Wenatchee River above Derby Creek

This station was located on the Wenatchee River above the Derby Canyon Rd. Access was gained by parking next to the railroad tracks on the left bank and walking down a steep access road to the river. This station was originally installed in April, but the instream tidbit was lost during the high June flows. The instream tidbit was replaced on 7/17 at 16:37 hours. The instream tidbit was found dry on 8/7 and was subsequently moved into deeper water during that same visit. After looking at the thermograph the total dry period data was removed from 8/1 00:00 hours to 8/7 16:00 hours. The air temperature record begins on 4/27, the water temperature record begins on 7/17.

Wenatchee River above Peshastin Creek

Access to this station was approximately 300 feet downstream of a power line crossing through private property that changed landowners during the course of the study period. The adjacent land to the stream station was only growing grass during this study period, but may have orchard trees planted on it in the future by looking at the irrigation setup that was installed. The station was installed on 6/27. The tidbit was kept in the main channel of flow for the duration of the study period, only on 10/11 was it disturbed by someone who pulled it out of the water on the bank where it was found on 10/17 when it was removed. All data from 10/11 00:00 hours thru 10/17 was cut from the final dataset.

Peshastin Creek near mouth

This station was located on Peshastin Creek approximately 300 feet downstream of the last bridge crossing off the road that goes into the Department of Transportation Pit Slide gravel area and the right bank access for the Dryden dam. The instream tidbit was in the main channel of flow for the entire study period. The original instream tidbit was lost in the high June flows and was replaced on 7/17. No other problems were encountered during the study period.

Wenatchee River above Ollala

This station was located next to a rafting pullout along Stines Road approximately 0.18 river miles downstream of the Highway 2/97 bridge crossing. It was attached to a concrete block and was moved several times as the water stage receded. On 8/6 at 17:15 hours it was found dry, and was moved as far out as possible until the water was too deep to wade. The thermograph shows the instream tidbit going dry sometime after 17:00 hours on 8/2 so the water temperature data was cut from 8/2 17:00 till 8/6 18:00.

Wenatchee River above Mission Creek

This station was located approximately 0.37 miles above the mouth of Mission Creek next to the railroad. Immediately above the tidbit station is a sandstone formation that has lots of shelves and pockets that have a very high roughness factor. The tidbit was anchored with a concrete block and thrown in from the right bank side. There were no periods where the tidbit went dry and no other data qualifications are necessary.

Mission Creek

This station was located approximately 30 feet downstream of the Sunset Avenue bridge crossing (above Brender Creek). The instream tidbit was 0.07 feet from the water surface during the 8/15 download check, and there was a water temperature spike on 8/14 that may have been influenced by the instream tidbit being directly exposed to air temperatures, except that a comparison with the air temperatures shows that the recorded instream temperatures were much different (max instream temperature was 26.85 degrees Celsius and the corresponding air temperature was 32.47 degrees Celsius). A comparison with the flow record from the continuous gage (45MC00.1g) showed a drop in stage (stage heights less than 0.65) that correlated with the same time as the high temperatures recorded from approximately 4:00pm to 7pm, however the gage had a much lower instream temperature for this time period (16.4-17.6ºC, with the high reading occurring at 5:30pm, the same time as the max temperature recorded by the tidbit) and this gage is also influenced by Brender Creek. The low stage combined with debris that piled up around the instream tidbit likely produced slightly higher temperatures than the average stream temperature for this reach.  Since the stage recordings show that the creek was at or below 0.65 for most of 8/14, the entire temperature set for 8/14 was cut from the final record.

<u>Brender Creek</u>

This station was located right above the Sunset Avenue culvert crossing Brender Creek.

<u>Wenatchee River at Monitor</u>

This station was located on the right bank of the Wenatchee approximately 400 feet upstream of the boat launch in Monitor.  The first instream tidbit installed was lost during high June flows, and the second instream tidbit was lost due to apparent signs of vandalism.  A third tidbit was installed on 8/7 and no further problems were encountered with the instream tidbit for the remainder of the study period.  The air tidbit had no problems and the data record begins 4/27. There was a period of several days from 6/14-6/20 when the air tidbit was under water (it was originally installed 4.2 feet above the wet edge) and there were physical signs of debris in the shrubs in which the air tidbit was installed;  this data period was cut from the air temperature record but kept as an addendum of water temperatures since the original water tidbit was lost during this time.

<u>Highline Irrigation Ditch return at mouth</u>

This station was located approximately 20 feet downstream of the end of the concrete channel (the return flow channel coming from the Wenatchee Reclamation District office) and approximately 30 feet upstream of the confluence with the Wenatchee River.  The first installed instream tidbit was not recovered during the 7/25 download check (vandalism is assumed since stream velocities at this site should not have been fast enough to tear off the shade device and tidbit during the high June flows).  A second tidbit was installed and no problems were encountered for the rest of the study period.  Dry periods were determined to be 9/4 10:06am through 9/5 9:36am, 9/18 10:06am through 9/19 9:36am, 10/9 10:06am through 10/10 9:36am. The irrigation ditch was closed on 10/16.

<u>Wenatchee River near mouth</u>

This station was located on the Wenatchee River approximately 30 feet downstream of the pedestrian bridge at the Confluence State Park.  During the course of the study period it was observed that the river was influenced by the Columbia river at this site due to the dam downstream of the city of Wenatchee.  This impoundment changed the river stage of the Wenatchee at this station independent of the Wenatchee's instream flow, and it is unclear how much that affected the tidbit data at this site.  There was no tidbit located on the Columbia River upstream of the confluence with the Wenatchee River.  There was a period from 8/3 8:00am through 8/7 8:30 when the instream tidbit was dry; it was found dry on 8/7 and moved into deeper water.  No other problems were encountered with the instream tidbit during the study period.  There was a problem re-launching the air temperature and relative humidity sensor in the field, so that dataset is only for the period from 6/29 through 8/29 and there is no data past 8/29.